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Simulating the Helicopter-Ship Interface as an Alternative to Current Methods of Determining the Safe Operating Envelopes

by

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In the past decade, there has been a dramatic increase in the use of helicopters in conjunction with non-aviation ships by the U.S. Navy. Landing the helicopter on the ship in the presence of high winds and stormy seas can be a hazardous process. The safe operating envelopes are determined at sea by the Naval Air Test Center and is a slow laborius and expensive process. Moreover, there is a substantial backlog of about eleven helicopters and twency ships that, at the present rate, cannot be cleared in this century. This has led to the suggestion that the problem might be solved by simulation, and it is with this suggestion that the present paper is concerned.

1. The airflow to the ship can be predicted sufficiently accurately.
2. A good basic ship motion prediction exists, but requires somefurther development and validation with real ships.
3. The ship airwake is almost unknown and previous attempts to analyze it were faulty.

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4. Further work is required on turbulence modeling of helicopters.

5. Before it is possible to determine the size of computer necessary for simulation, it is necessary to determine the extent to which the mathematical model of the helicopter and the physical model of the complex fluid flowfield can be simplified, while still retaining the fidelity of the helicopter motion.

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List of Figures

List of Tables

CONTENTS

INTRODUCTION

The increasing use of helicopters in conjunction with non-aviation ships poses many major problems, particularly during the landing phase of operations in the presence of high winds and rough seas. Excessive motions of the ship combined with the highly turbulent air-wake from the ship's superstructure can make landing the helicopter a hazardous process.

The reason for this problem is, of course that, when the ships were designed, the operation with helicopters was not foreseen and, furthermore, the U.S. Navy has been remarkably slow to adopt well stabilized ships.

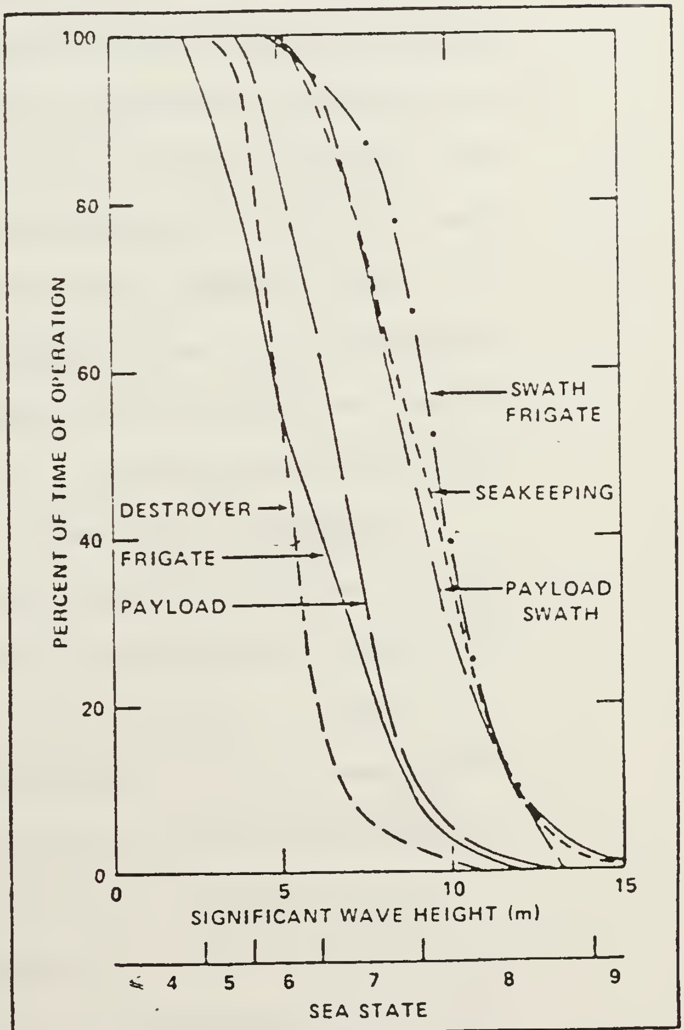


Figure 1. Percent of Time of Operation in the General North Atlantic-Winter as a Function of Significant Wave Height for Six Hullforms

It will probably come as a surprise to many readers that a helicopter can operate from a 125 m.(400 ft.) frigate in the North Sea a mere ten percent of the time in winter. The reason is partly wake turbulence but primarily ship motion. Two recent papers concerned with the theory, practice and value of reducing the latter are by Brown (1985) and Bittner and Guignard (1985).

McCreight and Stahl (1985) compare the seakeeping qualities of different hulls and Figure 1 shows the percent time of operation as a function of sea state for six different hulls.

The remarkable performance of the SWATH (Small Waterplane Area Twin Hull) frigate is a hopeful harbinger of the future. Prina (1985) gives an account of its history and the DOD plans for it in the near future. Unfortunately, its acceptance is not universal.

In the visible future, however, there remains the problem of successfully interfacing the mono-hull with the helicopter. Carico, McCallum and Higman (1985) indicate that this task involves eleven different helicopters and twenty different ships.

At the present time, the safe operating envelopes for the helicopters are determined by the NATC at sea for every ship-helicopter combination - a slow, laborius and expensive process. A description of the testing process is given by Madey and Whitmer (1983). The efforts of the N.L.R in the Netherlands are more scientific in nature and are outlined in the paper by Hofman and Fang (1984). However, the N.A.T.C. has plans to instrument the helicopter in the future.

Suggestions for future directions of this test process are made by Carico and Madey (1984) ; these include supplementation and/or replacement of the test process by simulation.

Even if the high cost of $75,000 to $150,000 per combination is disregarded, it is estimated that,due to the unavailability of ships, all the operating envelopes cannot be determined this century.

This predicament led to the suggestion that the problem may be solved by simulation which, if possible, would allow the training of pilots, in addition to mapping the interfaces. The simulation would require that the ship motion, the airwake from the ship's superstructure and the helicopter motion all be predictable for a generic ship and helicopter. It is with that suggestion that the present report is concerned.

The interface problem has been analyzed before, the most recent effort being by McEligot (1983), where a description of past attempts and references not in the present report appear. These attempts seem to acknowledge, in an uncertain way, the role that atmospheric turbulence might play but recognition of the effects of atmospheric shear is non-existent.

The succeeding sections of this report consider the current ability to predict the freestream airflow to the ship, the ship motion, the air-wake of the ship, the motion of the helicopter, and the existing simulation capability. Treatment of the first three topics is considerably more exhaustive than the last two.

1 THE FREE-STREAM AIRFLOW TO THE SHIP

i The Most Important Parameters

It would be inappropriate here to enter into a detailed discourse of atmospheric turbulence. This subject is very adequately covered by Houbolt (1973), Panofsky (1977) and Davenport (1983).

The high winds that are relevant to the interface problem are called neutral density by Meteorologists. Fortunately, for this regime, there are available much statistical data and empirical relationships, although there is some scatter in the data at low frequencies.

According to Carico (1986), one of the greatest sources of error in dynamic interface testing lies in ship anemometers that do not give the freestream airspeed to the ship. Apparently, due to interference from the flow around the superstructure, the readings are usually faulty and ship personnel have little confidence in them.

The parameters that are of significance to the free-stream airflow towards the ship are

1 The windspeed averaged over a period of time, somewhere between ten minutes and an hour, the actual period making little difference. This is called the mean speed.

2 The standard deviation σ of the longitudinal (along wind) windspeed fluctuations about the mean which, when divided by the mean speed, yields the parameter "turbulence intensity".

3 The longitudinal scale length of the turbulence, which is a measure of the mean length of the most energetic eddies in the turbulence.

This is also called the "integral" scale length to distinguish it from other micro-scales, which are less important here.

4 The spectrum function of the turbulence, which indicates how the energy is distributed amongst the frequencies present in the turbulence. An alternative to this is the autocorrelation function from which the spectrum function can be derived.

Empirical relationships are available (E.S.D.U. data items 74030,74031) for the above four parameters as a function of

1. the mean windspeed,
2. the elevation and
3. the roughness length scale.

The latter scale, usually designated z_0 (meters), is a measure of the ground roughness and its value has no direct relationship to the height of obstacles on the ground. For example, for very smooth surfaces like ice or mudflats, z_0 is about 0.0001 m.; for an airport runway area, the value is about 0.05 m., while in a built up urban area it is about 3.0 m.. More details are given in Figure 2. The values for sea surfaces will be discussed later.

Four graphs, Figures 2 through 4, taken from E.S.D.U. 74031, and Figure 5, allow the above four parameters to be estimated, using empirical data. The following development is an attempt at analysis.

Garratt (1977) gives the relationship linking the drag coefficient for the neutral airflow over the sea and the mean speed :

Figure 2 Surface roughness parameter z_0 (from ESDU 74031)

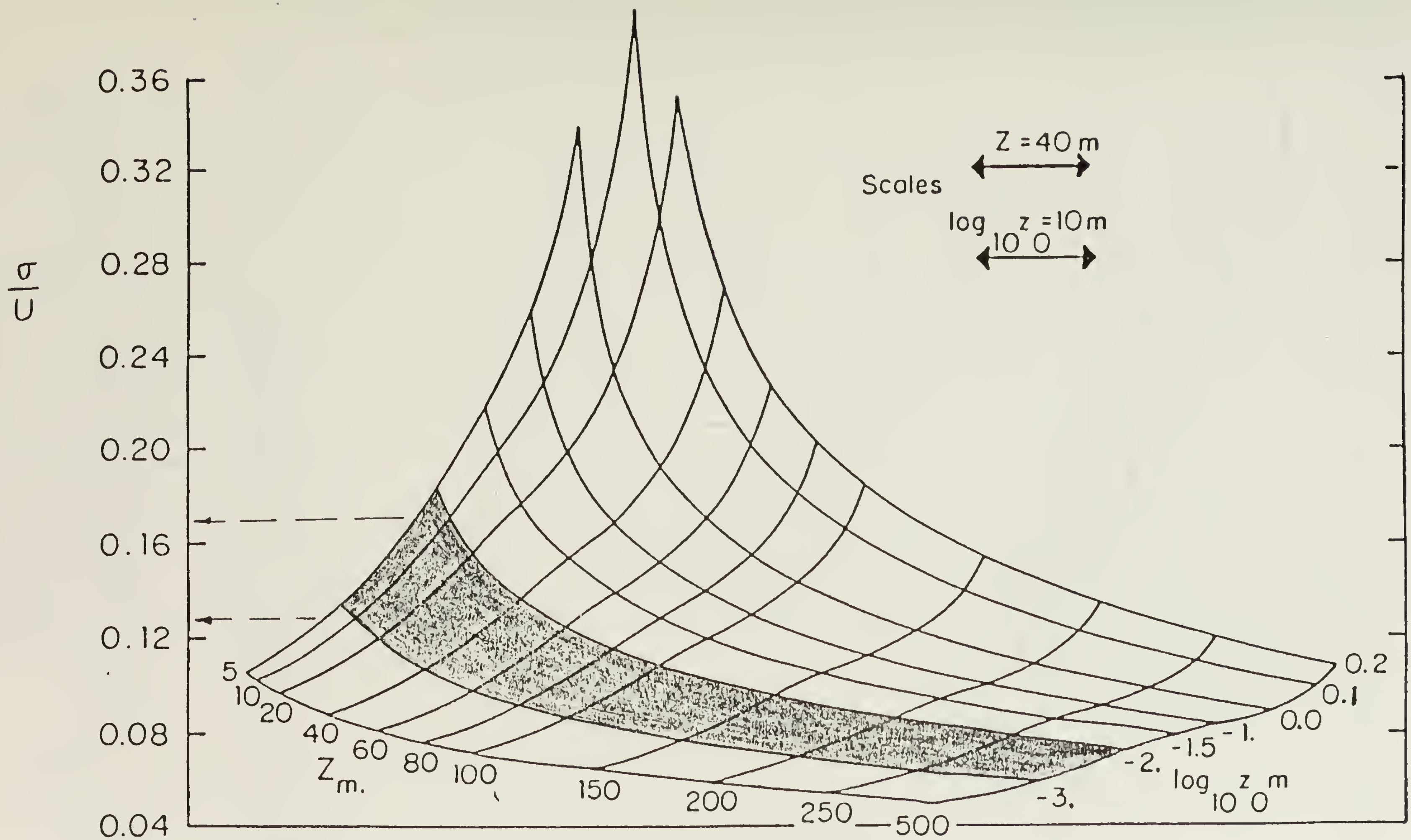


Figure 3. The (longitudinal) Turbulence Intensity
(from E. S. D. U.)

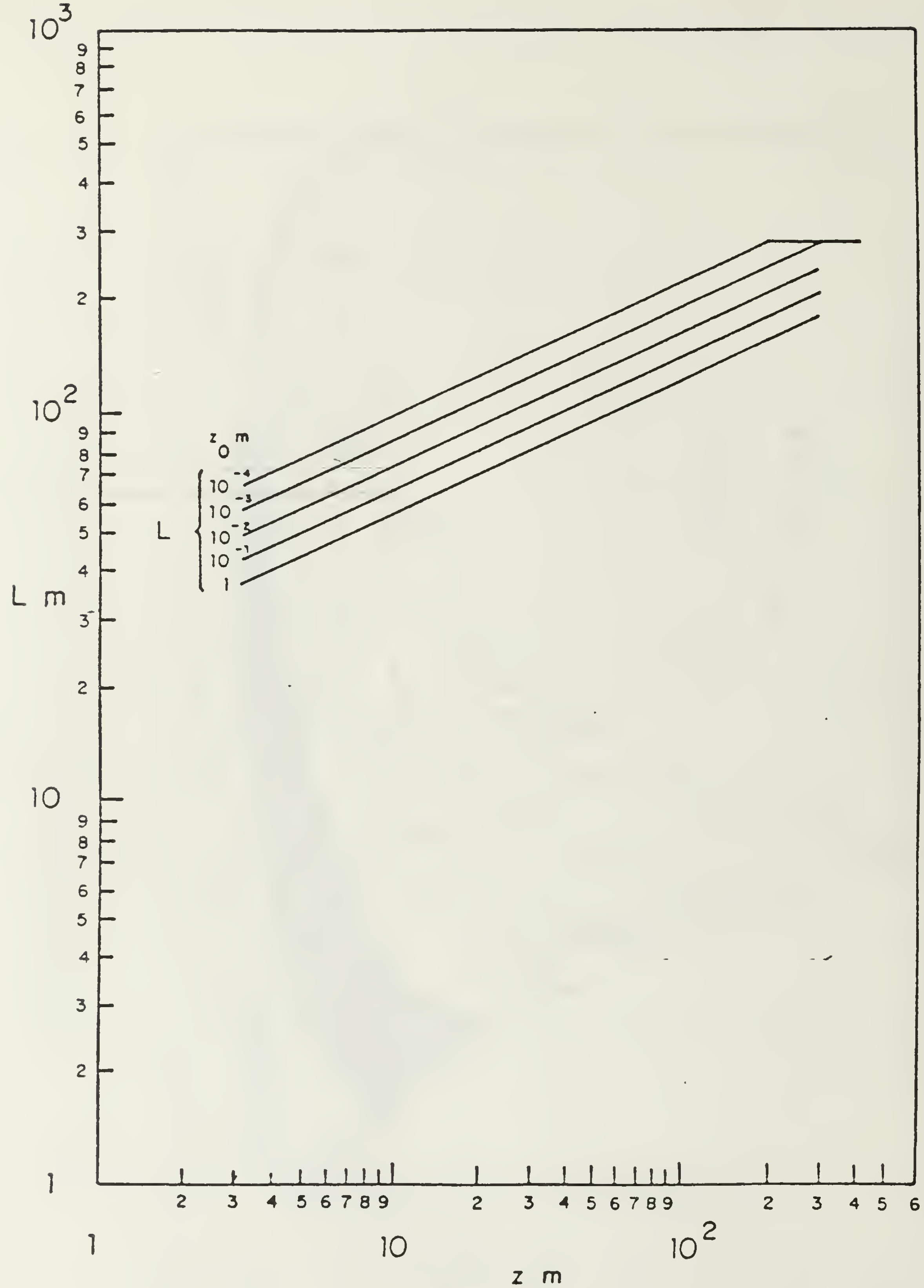


Figure 4 Values of the Length Scale Parameter L

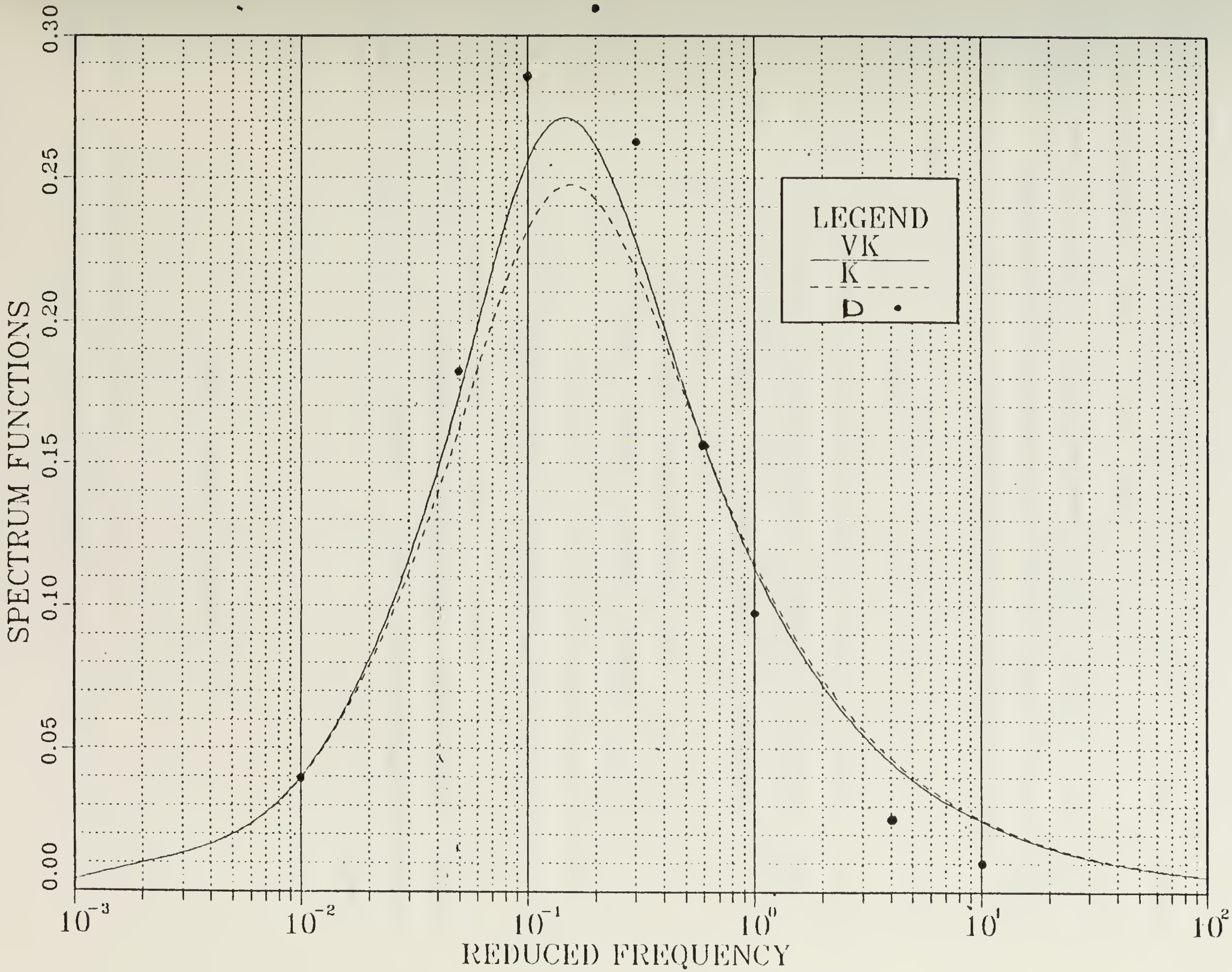


Figure 5. The Spectrum functions of Von Karman ——, Kaimal ----, Dryden •.

$$C_{d_n} = (0.75 + 0.067\ U(10))\times 10^{-3} \quad ....(1)$$

The mean windspeed here is the value of U at the 10 m. altitude, which is typical of the helideck height of a cruiser (USS Ticonderoga).

From the Monin-Obukov similarity theory

$$k\ /\ \surd(C_{d_n}) = -\ln(Z/z_0)\ , \quad ....(2)$$

where k is the Von Karman constant and is closely 0.41,

Eliminating C_{d_n} between Equations 1 and 2 yields

$$z_0 = 10\ \exp(-0.41/\surd(0.75 + 0.067\ U(10))\times 10^{-3} \quad ....(3)$$

This is the roughness length of the sea surface as a function of the mean windspeed at ten meters elevation. Garratt reports that the effects of fetch, wind duration and unsteadiness are obscured in experimental scatter. This expression is, therefore, intended to be an approximate and general one.

ii The Turbulence Intensity Levels

The E.S.D.U. data item 74031 gives the turbulence intensity as a function of altitude and roughness length scale only ; this is shown here as Figure

3. However, Thompson (1985) indicates that this data item is about to be revised. The new results show a weak dependence of the turbulence intensity on mean windspeed as well. In the present preliminary discussion, this small difference is ignored. The largest mean windspeed that is likely to be of interest in the interface problem is about 25 m/sec (about 50 knots) and for this value at ten meters altitude, Equation 3 yields 0.0024 m. for z_0. Data item 74031 (Figure 3 here) gives the value of 0.14 for the turbulence intensity.

Davenport, however, indicates that roughness lengths of 0.001 to 0.01 m. are usual for rough seas. The above value, of course, falls in this range. For this range of roughnesses and the 10 m elevation, the turbulence intensity range, from Figure 3, is 0.13 to 0.17.

These values represent very turbulent flow indeed ; the fluctuations of the speed about the mean is approximately Gaussian and, using such statistics, one finds that 84 percent of the fluctuations about the mean of 25 m/sec lie in the range 25-25x0.17 to 25+25x0.17 i. e. 20.75 to 29.25 m/sec.

The distribution of the windspeed fluctuations in the atmosphere is known to deviate somewhat from the Gaussian ; Reeves, Joppa and Ganzer (1976) show how non-Gaussian effects are modeled. However, these effects are irrelevant to the ship airwake.

iii The Turbulence Length Scales

From Figure 4, for an elevation of ten meters and the range of surface roughnesses $0.001 < z_0 < 0.01$ the longitudinal scale of the turbulence is $80 < L < 90$ meters.

It is not the length scale itself that is very important, but the ratio of the length scale to a characteristic body dimension e.g. the beam of the ship. For comparison, the beam of the USS Ticonderoga is about 17 m.,giving a ratio of about 5 . The larger this ratio is, the more like a time-dependent non-random flowfield the actual flowfield appears to an observer on the ship.

It should be emphasized that there are also fluctuations in the wind velocity components in the lateral and vertical directions normal to the wind direction. Associated with these directions are turbulence intensities and length scales which are not very relevant to the present discussion.

iv The Mean Speed Profiles

The lower level of the atmosphere is essentially a boundary layer, with the velocity varying from zero at the surface to the "gradient velocity" U_g at the "gradient height" Z_g. The gradient velocity is the tangential velocity of the wind about the storm center and the gradient height for rough sea is about 250 m. Davenport gives the commonly used expression

$$U / U_g = (Z / Z_g)^{0.11} \quad \text{.......................(4)}$$

If the velocity is known at any particular elevation, these values may be used instead of U_g and Z_g in Equation 4. For example, if U = 25 m/sec at 10 m. elevation , then

$$U = 25 \ (Z/10)^{0.11} \text{m/sec.} \quad \text{................(5)}$$

This is the mean speed profile as a function of elevation Z for the given conditions. It should be noted that Z is an effective height and is defined as the actual height above the ground minus the "general obstruction height" . To be meaningful Z should be much greater than the general obstruction height or, in the present case, the wave height. Furthermore, near the level of the wave tips, the air is likely to have considerable spray contamination.

V The Spectrum Function

The most frequently used spectrum function, and one for which an analytic autocorrelation function is available, is the Von Karman :

$$\frac{n \ S(n)}{\sigma^2} = \frac{4 \ \tilde{n}}{(1 + 70.8 \ \tilde{n}^2)^{5/6}} , \quad \text{................(6)}$$

where $\tilde{n}$ = n L/U, n is the frequency and other terms as defined earlier.

The Dryden spectrum function , frequently used because of its simplicity, is given by

$$\frac{n\,S(n)}{\sigma^2} = \frac{4\,\tilde{n}}{1 + (2\pi\,\tilde{n})^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The accuracy of the this function falls off with increasing frequency. Both functions are shown in Figure 5.

vi Modeling the Free-Stream Airflow to the Ship

Strictly speaking, when the freestream airflow to a ship is to be modeled in a wind tunnel, the mean speed profile, the turbulence intensity, the ratio of the turbulence length scale to the ship's beam and the spectrum function should be similar to the real flow. In experiments carried out on ship airwakes to date, this has certainly not been the case.

White and Chaddock (1967) attempted to model the flow around an aircraft carrier (USS Lexington) in a wind tunnel with a uniform velocity distribution and a 0.3 % turbulence level ; they found that it did not model the real flow. When Loezos (1967) attempted to correlate the turbulence intensities on the real carrier with those from the same wind tunnel, he found the intensities on the carrier much larger generally, often by a factor of three. Weir (1966) conducted some water tunnel experiments on a model of the same carrier and also concluded that the flows were not similar.

Nevertheless, experimentation in "ordinary" wind tunnels has been continued by Garnett (1976,1979) and Hurst and Newman (1985); the latter claim to have found good agreement between the model and real flow at two points. However, while disagreement at two points may be considered adequate to disprove a hypothesis that two flows are similar, agreement at two points cannot be expected to prove that they are. Loezos found fair agreement at one point and probably could have found another if he had looked hard enough.

Figure 6 shows the stations at which the measurements were made on the carrier and model for the White and Chaddock, and Loezos, analyses and Figure 7 shows turbulence intensity found by Loezos at station 2. The intensity on the carrier was about three times that on the model. Stations 3 and 14 showed similar results; there was fair agreement at station 1.

When performing interface tests at sea, in the case of the Lexington and in tests since, only the relative ship-wind velocity, as measured by the ship's anemometer, is actually recorded. Unfortunately, this can lead to errors in the results. If turbulence and shear are not considered it is immaterial how the relative velocity vector is formed. If they are, however, since the wind component only has the turbulence and shear, this component must be separated out from relative velocity.

The wind tunnel tests of the model of the Lexington in very low turbulence flow without shear would be a reasonable model of the the flow around the carrier moving, at the relative speed used, into a zero velocity wind. Since the measurements of the turbulence intensity on the Lexington were much greater than those on the model, it is likely that the relative wind measured on the carrier had by far the greater contribution from the wind velocity i.e. the ship was probably moving very slowly. The greater the contribution of the wind velocity to the relative velocity, the more turbulent the airwake is likely to be and, in a given region near the ship, the higher the PRS rating that will be assigned in the test. If, when the tests are carried out, the relative velocity is composed solely of the wind velocity, the PRS ratings will be conservative. On the other hand, if the ship velocity has a large contribution, those test results will be very optimistic.

It is not surprising that such confusion should exist in the field of aerodynamics ; the classical aerodynamics journals have tended to consider the classical aerodynamics of uniform speed, low turbulence flows and, even when turbulence is considered, it is usually in the context of buffeting and/or aeroelastic effects. Atmospheric shear has, however, in recent times been the focus of some interest. The only aeronautical engineering journal considering mainly atmospheric flows and their effects is the Journal of Wind Engineering and Industrial Aerodynamics. As will be seen in Section 3, this is also the major source of information on bluff-body aerodynamics.

Exactly which of the modeling conditions listed in the first paragraph can be relaxed, cannot be answered precisely at this stage. This problem will be considered further in Section 3.

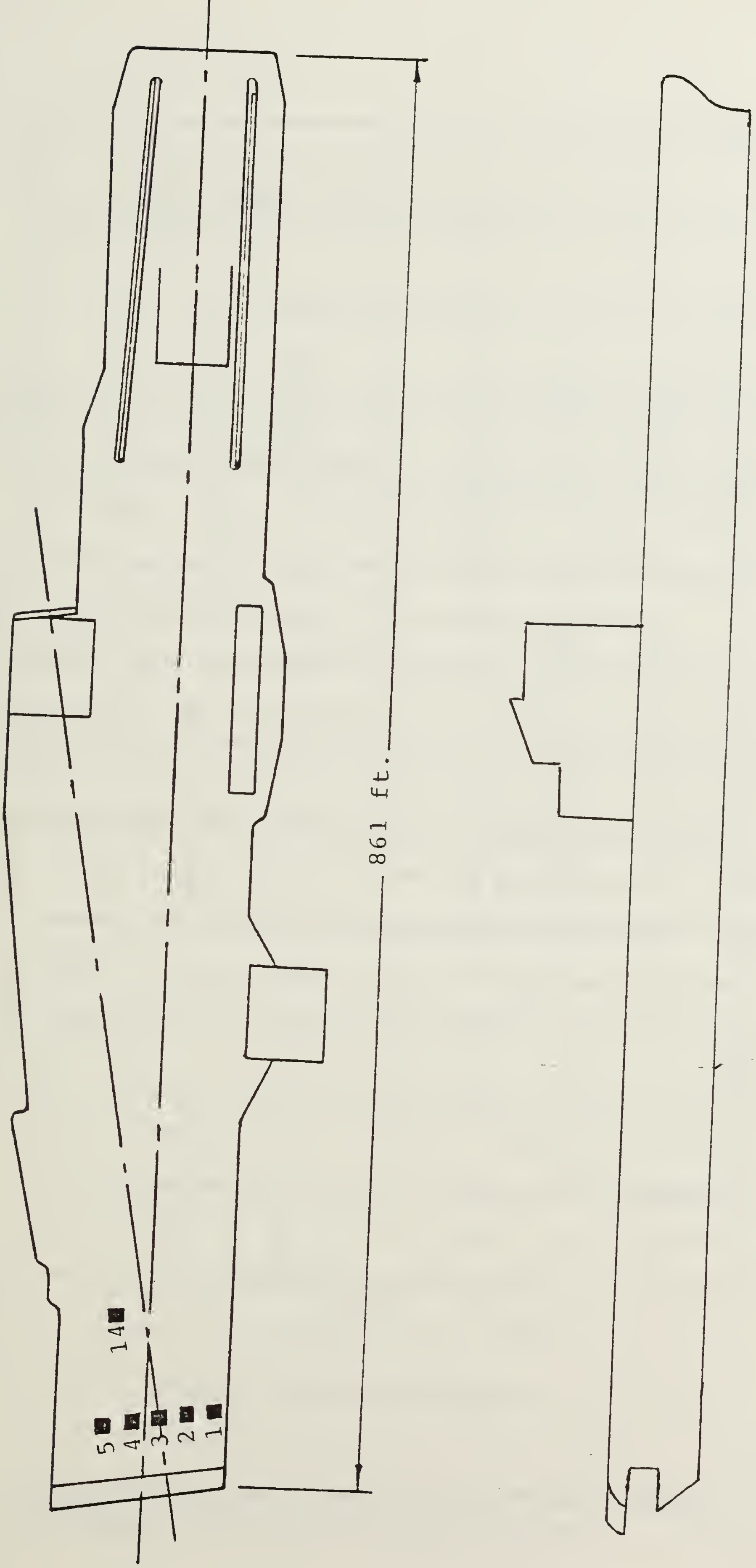


Figure 6 Planform of CVS-16 Showing Stations at which Data are Taken

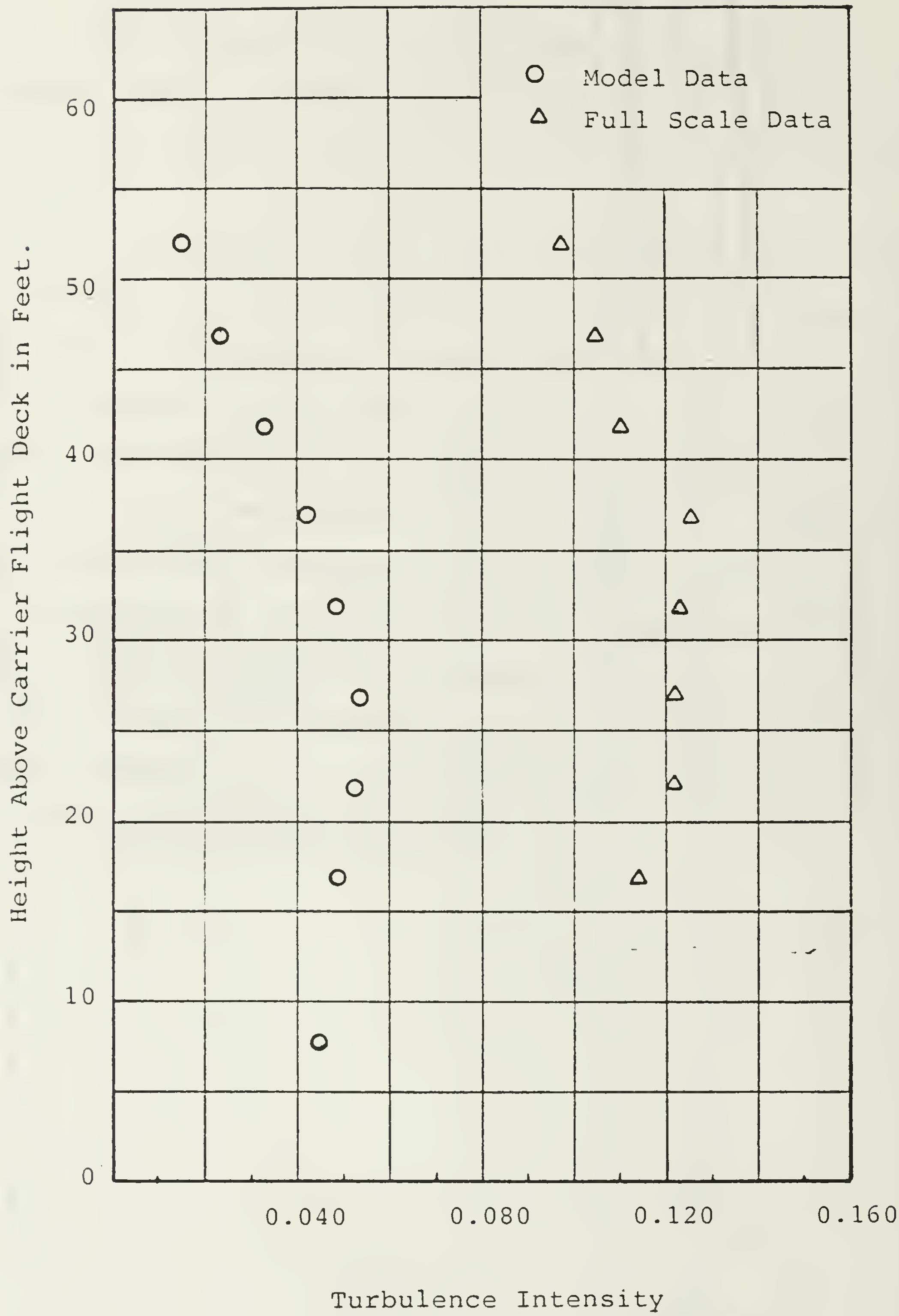


Figure 7 Full Scale and Model Turbulence Intensities vs Height above Flight Deck at Station 2 .

i THE SEA MOTION

The most frequently used physical model of wave motion on a deep sea is that of an extremely large number of waves all with different periods, random in phase and of small amplitude. Just like the windspeed fluctuations, the sea waves also have a spectrum function that indicates how the energy is distributed amongst the frequencies present.

This spectrum function shows that there is little energy in the waves at very low frequency; that the energy rises steeply with increasing frequency to a certain maximum and then tapers off fairly slowly. The frequency corresponding to these most energetic waves depends on a number of factors.

First, if wave motion due to tides and earthquakes is disregarded, sea waves are formed by air-sea interaction that manifests itself either by pressure effects or by viscous drag at the interface.There are numerous interaction theories, but the exact mechanism has proved very elusive.

The waves are usually divided into long- and short-crested ones. The long-crested are due to storm centers far away and propagate with long crests that form essentially parallel lines. The largest amplitude ship motions usually occur in such waves. Short-crested waves have no obvious fronts but do have a dominant direction. The crests never last long, but disappear and others form. These are the confused seas due to local winds and are the ones of greatest interest in the interface problem.

The rate at which energy is transferred from the wind to the water waves depends on the wind speed, on the length of contact (the fetch) and on the wave size.The latter develops with fetch and time to a "fully-developed" state that depends on the wind speed. Figure 8 shows how the wave spectrum develops ; there is a marked shift to the left of the peaks as the wave grows. This implies that there is a shift of energy towards the lower frequency waves; note that almost all of the wave energy is concentrated in the frequency band $0.3 < \omega$ rad/sec < 1.0 . Figures 9 and 10 show the growth of wave height with time and fetch. It takes up to about 24 hours and about 1000 km. for a wave to develop fully in a 40 knot (20 m/sec) wind.

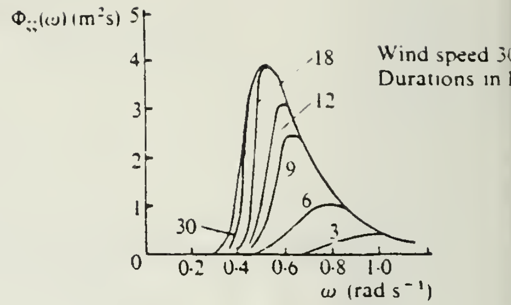


Figure 8

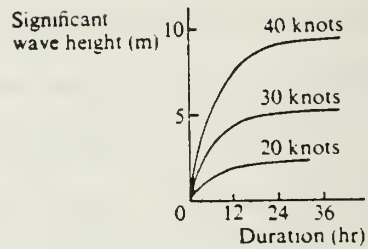


Figure 9

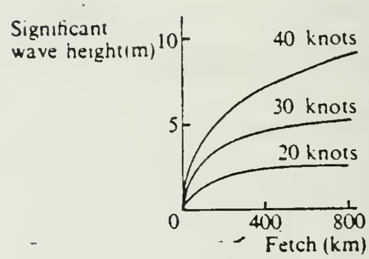


Figure 10

ii. THE SEA WAVE SPECTRUM FUNCTIONS

According to O'Reilly (1984), there are almost as many spectrum functions as there are Oceanographers. However, Brown and Camaratta (1978) indicate that the one parameter ones are suitable for fully developed seas only. They and Meyers, Applebee and Baitis (1981) at the DTNSRDC used the two-parameter Bretschneider spectrum. The two specifiable parameters are the significant wave height h (the mean height of the one third highest waves) and the modal period T_0 (the period of the peak in the spectrum). This spectrum function is

$$S(\omega) = [\ 483.5/(\omega^5 T_0^4)\ ].h.\exp[-1944.5/(T_0\omega)^4] \ldots\ldots\ldots\ldots\ldots (8)$$

The actual spectrum experienced by the ship will be somewhat different ; the ship's "encounter frequency" will depend on the "heading" - the angle between the ship direction and the dominant wave direction. Figure 12 shows an example of wave and encounter spectrum functions. These frequencies satisfy

$$\omega_e = \omega \pm (V\omega^2/g)\cos\mu\ , \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where ω is the wave frequency, ω_e is the encounter frequency, V is the mean speed of the ship, g is the gravitational acceleration and μ is the heading angle i.e. the angle between the ship direction and the dominant wave direction. A two-dimensional spectrum function would best describe the short-crested waves but an empirical relation involving the one-dimensional spectrum function and a "spreading function" is found to be simpler and adequate. The latter is $(2/\pi)\cos^2(\nu - \mu)$, where ν is the angle on either side of the dominant wave direction. The use of this expression is also supported by the International Towing Tank Conference (ITTC) and the International Ship Structure Congress (ISSC) and it is the basis of the short-crested wave representation in the DTNSRDC's ship motion program,.

It should be noted that the wind direction usually, but not always, coincides with the dominant wave direction.

Long-crested seas produce no ship roll response in head seas and no pitch response in beam seas. Short-crested seas, on the other hand, produce both both pitch and roll motions, regardless of heading.

iii. THE SHIP MOTION

a. Single Degree of Freedom Dynamic System

The simplest method of analysis of a vibrating body, essentially what moving ship is, is to use the simple linear spring-mass-damper model. A single mass constrained to move in one direction is a single degree of freedom (DOF) system. The equation of motion is

$$M\,y''(t) + D\,y'(t) + K\,y(t) = F(t), \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where, M is the mass, D is the damping coefficient, K is the restoring force per unit displacement , y is the displacement of the mass from its equilibrium position and F is the external forcing function. In the present case,the interest lies in forcing functions that are either sinusoidal or stationary random. Stationary random means that the statistical properties do not change with time ; hereafter, where random is written, stationary random is implied. The sinusoidal forcing function produces a sinusoidal (term includes cosinusoidal also) response and a random forcing produces a random response. When the response is random, the function y(t) cannot be precisely determined ; the best one can do is to predict it in a mean square sense. It is a most useful property of linear systems that, if the input is random with a Gaussian distribution, then the output is also random and has a similar distribution.

b. Multi-Degree of Freedom System

A number n of masses connected together by springs and dampers, or a structure with n nodes whose displacements are to be studied, represents an n DOF system ; each displacement requires a co-ordinate to describe, so n co-ordinates are required and Equation 10 becomes an n th. order one :

$$M\,Y''(t) + D\,Y'(t) + K\,Y(t) = F(t), \qquad \text{...............(11)}$$

where M, D and K are nxn matrices and Y and F are n-dimensional vectors. The i th. component of the vector F acts on the i th. component of Y i.e. on the i th. degree of freedom. The coefficients M, D and K may be constants or not and ,if $\bar{F}$ is a random vector, then Y is a random vector also. It should be noted that F here is a generalized force i.e. can be a force or a moment. Components of F that are moments correspond to components of Y that are angular displacements.

c. The Equations of the Ship Motion

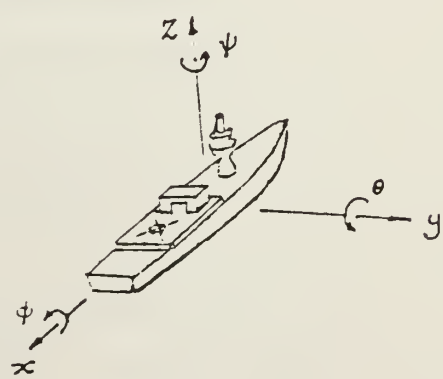


Figure 11

A simplified linearized ship motion model comprises a sixth order system, the six degrees of freedom for a point on the ship being :

3 translational - heave, sway and surge (z,y,x)

3 rotational - roll, pitch and yaw (ϕ, θ, ψ).

These are illustrated in Figure 11.

The linear system is now given by Equation 11, where the coefficients are 6x6 matrices, F is the six-component vector, whose three forces and three moments arise as a consequence of the irregular motion of the waves near the ship, and Y is the vector (x,y,z,ϕ,θ,ψ). The present problem is now more complex than the mechanical one with six each of masses,dampers and springs.

The water surrounding the ship will have some motion components that are in-phase with the motion of the ship, thus giving the ship, as a system, "added" masses and inertias. This leads to a "virtual" mass matrix, whose elements are the sums of the ship mass and inertias and the added mass and inertias. This matrix can be computed by a method to be described in the next subsection, once the mass distribution of the ship and the hull geometry are known.

The hydrostatic restoring force coefficient matrix K can be calculated, once the hull geometry is known.

The damping matrix is the most complex, comprising contributions from

1. External viscous terms arising from skin friction on the hull,keel, rudder, fins, etc.
2. Internal viscous terms arising from motion of water in bilge-keels (if any).
3. Speed-dependent terms arising from dynamic lift and
4. Wave- and eddy-making activities of the ship.

d. Theoretical Computations of the Coefficients and Forces

In reality, the flow of water around a ship is viscous, 3-d and with a free surface, which normally requires the full Navier-Stokes equations. These, however, require very large-scale computation and many approximate methods have been developed. The "strip theory" approximation is one of the most frequently used and involves such approximations as beam/length ratio << 1 (for most ships this ratio is about 0.1), inviscid flow, etc. See Blevins (1977,p332) or Price and Bishop (1974,p220). This strip theory, well-known to Aerodynamicists, involves dividing the ship from stem to stern by transverse planes and treating the sections between the planes with two-dimensional potential-flow theory. In this way, the added terms in the mass matrix, the inviscid contributions to the damping coefficient and the forces and moments on the hull can be calculated. The remaining terms in the damping coefficient are either empirical or semi-empirical.

e. Computation of the Displacements

The sixth-order system of Equations (11) for the ship are usually coupled to some degree i.e. at least some of the equations have to be solved simultaneously. Roll, sway and yaw often couple together, as do heave, pitch and surge. Roberts and Dacunha (1985) found that, by means of a simple transformation, the roll motion can be decoupled. This transformation simply moves the co-ordinate reference frame from the ship's center of gravity to a "roll center".

The linearized system of equations, strictly speaking, is valid only for small motions of the ship about its equilibrium state. The accuracy of the predictions fall off as the amplitudes of the motions increase ; this usually occurs first for the rolling motion. Meyers et al (1981) found an iterative method of estimating the non-linear roll damping coefficients and thus made corrections for large roll amplitudes. The so-called "free-decay" experimental method, in which a ship model is given a displacement from the equilibrium state and allowed to oscillate freely back, is frequently used to measure damping coefficients. Roberts (1985) found that such tests can yield very good estimates of the damping parameters well into the non-linear range. The two Roberts' papers suggest that the roll equation can be separated out from the others and full non-linear rolling motion predicted.

Since the coefficients and the forcing functions are known from subsection d above , it is possible, at least numerically to solve the sixth order system of Equations 11 for the rms values of all six displacements. In some circumstances, when two or three modes only couple, analytic solutions are possible.

Since the fluctuations in the wave amplitudes have a Gaussian distribution and the peaks have a Rayleigh one, modeling the ship motion with a linear system implies that the fluctuations in the ship motion will have a Gaussian distribution and the peaks in the ship motion will follow a Rayleigh one.

The above approach (Secs. d and e) is called the "time-domain" approach. A somewhat different, and an equally frequently used method, is called the "frequency analysis" method. It is the basis for the NAEC ship motion program by Brown and Camaratta. The DTNSRDC's SMP program uses both methods.

f. The Frequency Analysis Method

Once the sea wave energy spectrum is known, the energy in a bandwidth $\Delta\omega$, about a specified frequency ω, is given by the area under the curve. The ship experiences frequencies somewhat different from the wave frequencies. The actual encounter frequency was described in the last section. In Figure

12, if A is the mean sea wave energy per unit bandwidth $\Delta\omega$ about the

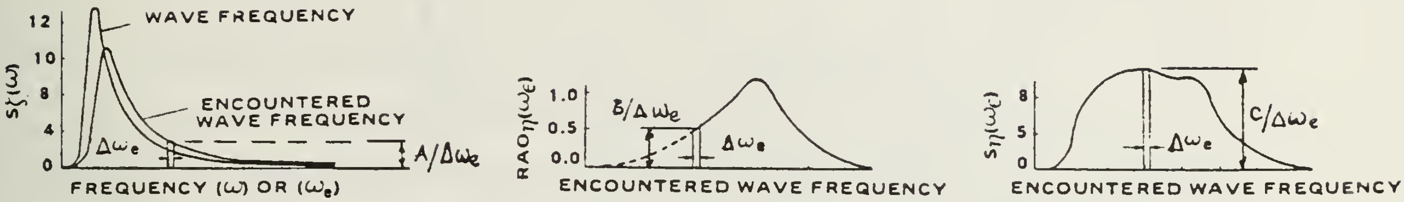


Figure 12

frequency ω and C the corresponding value of the ship response of any particular degree of freedom, then B = A / C is the value of the Response Amplitude Operator (RAO) at that frequency. Thus the RAO is simply a scaling factor between the encounter energy and the ship response energy at a given frequency. Obviously, in general, the RAO is a function of frequency and varies continuously over all the frequencies present in the waves.

The RAO is the name given by Naval Architects to the square of the quantity well-known to most engineers - the transfer function. Typical wave, encounter and response spectrum functions and the corresponding RAO are given in Figure 12. As shown on the diagram, in order to define the output spectrum, an RAO function is required for each ship, each heading, each ship speed and each DOF.

Measurement of the RAO's is a relatively simple matter for a given ship but, in view of the very large number required, it is a laborius business.

Figure 13 shows typical RAO's for the six degrees of freedom and various ship headings μ of a given ship, ship speed and sea condition. By convention ,the heading 0 degrees is a following sea, 90 degrees is a beam sea and 180 is a head sea. It is emphasized that, for a specified ship, one such diagram is required for each sea condition and ship speed.

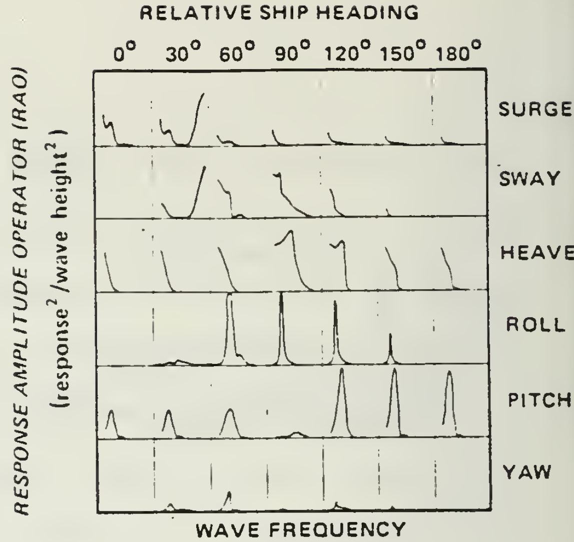


Figure 13

Rolling and pitching are narrow band processes, which implies that they are lightly damped and, hence, each has a spike in the spectrum function at the corresponding natural frequency. This indicates that, particularly for roll, large amplitudes can be caused by waves carrying significant amounts of energy at frequencies near the ship's natural rolling frequency.The situation is similar for pitching motions, but rolling is more frequently the limiting factor, particularly for non-stabilized ships.

O'Reilly describes in detail how the RAO's are used to drive the deck of a ship in a simulator.

g. Computation of the RAO's

The transfer function for a single DOF system is well known (See Tse, Morse and Hinkle (1966)) as

$$1/(M\,\omega^2 + D\omega + K).$$

For the multi DOF system, described by Equation 11, the transfer function is similar in form, but now the reciprocal is an inverse, since the terms in the denominator are matrices.

Thus, the transfer functions, and hence the RAO's, are readily found, once the coefficients are known from Section d. above.

iv. EXISTING SHIP MOTION PREDICTION PROGRAMS

There are at least 3 ship motion programs in existence

1. NMIwave, by the National Maritime Institute in England.

2. The NAVAIRENGCEN ship motion program, written by Brown and Camaratta at N.A.E.C., Lakehurst, N.J.and apparently based on an early DTNSRDC model.

3. The DTNSRDC's SMP, written by Applebee, Baitis and Meyers.

1. At the time of writing there was no information to hand about NMIwave.

2 The NAEC program is a relatively simple one that derives the mean square responses for the displacements, velocities and accelerations for the six DOF's at the ship's center of gravity and provision is made for computing the motions of any point on the ship. Outputs are available in both time and frequency domains.

The principal assumptions made in the program are

a. Both wave and ship motions are stationary Gaussian processes.

b. Ship motion is predictable by the linearized equations of motion.

c. The RAO's are available for the ship.

d. The Bretschneider spectrum is applicable.

The authors indicate that the program is expected to predict the responses of ships operating in seaways characterized by long-crested waves up to 16 feet in height. A number of correlation studies have been carried out that show satisfactory results for pitch and heave motions in head seas and in "oblique" waves. Some discrepancies were noted for the case of following waves and in the very low frequency range.They also claim that roll motions can be predicted with reasonable accuracy for moderate ship speeds in beam seas.

Although, in general, a commendable effort, the use of terms like "satisfactory results" and "reasonable accuracy" are a poor substitute for graphs showing the predictions of the program and the actual response of the vessel concerned.

3. The DTNRDSC's ship motion program is a much more sophisticated one. Given the hull geometry, the mass distribution of the ship, the sea condition and the ship speed and heading, the rms responses and the RAO's can be computed for a number of points on the ship.

The principal assumptions in this SMP are

1. Monohull ship form.
2. Strip theory is applicable.
3. Linearized equations are valid, though non-linear roll effects are accounted for.
4. The RAO's are derivable from harmonic inputs (from the waves) and outputs (the ship motion).
5. Heave, pitch and surge are uncoupled from roll, sway and yaw.

The hydrostatic calculations are first carried out and the following quantities, which depend only on the underwater hull geometry, are computed : the added mass and damping matrices and the exciting forces for all DOF's, ship speeds, headings and wave frequencies. This is a very time-consuming process and the results are stored in a file called COFIL ; many calculations for this particular hull geometry can be performed in a relatively short period once COFIL has been set up. Figure 14 shows the SMP flow diagram and, from it, the next step allows direct computation of either the roll motions only (options 3 and 5) or the rms values of the ship motion.

Useful outputs from the SMP include the speed-polar plots giving, say, the rms roll or pitch angles as a function of ship speed and heading.

The authors report that a problem arises with the SMP for quartering and following waves. For certain combinations of speed, heading and wave frequency, the surge, sway and yaw motions become unrealistically large due to the lack of restoring terms in the corresponding equations. Empirical limits derived from model data are placed on these three responses.

Examination of the DTNSRDC reports by Baitis, Meyers and Applebee (June 1981) and Baitis, Applebee and Meyers (July 1981) shows that agreement between the results of model tests and the predictions of the SMP is generally good. The pitch predictions are consistently very good, but the other motions lack consistency ; for some conditions the agreement is excellent and for others it is poor. A more recent report by Meyers and Baitis (Sept. 1985) indicates that an error was found in the bilge keel calculations and that the corrected SMP shows improved roll predictions.

To summarize, the SMP of DTNSRDC is a good basic program that needs some further development, fine tuning and, in particular, validation against real ships.

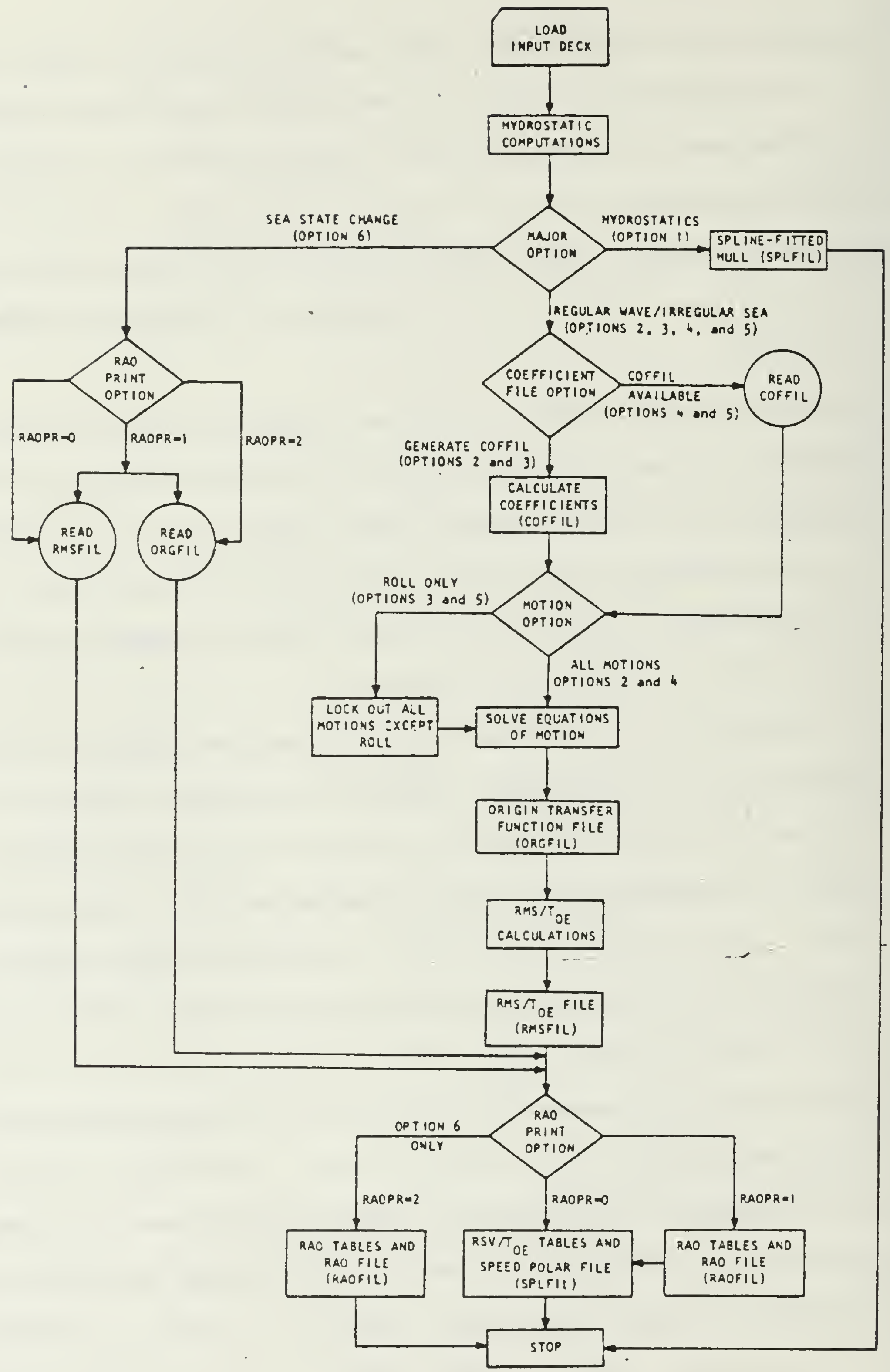


Figure **14** SMP Flow Chart with File Identification

V. FORECASTING THE SHIP MOTION

When attempting to land a helicopter on a ship, the pilot or deck officer, observes the motion of the ship and can with some reasonable accuracy predict the occurence of a lull in the motion. It would be extremely advantageous to be able to minimize the guesswork and predict the lull more accurately.

This problem presents a considerable challenge to a field known as "time series analysis". The question to be posed here is : given a sufficient history of the ship motion, can one predict its motion over the next t seconds, where ideally, t is at least 15 seconds ?.

Attempts have already been made by : Triantafyllou, Bodson and Athens (1982) ; Kaplan and Bentson (1982) ; Sidar and Doolin (1983) ; Paulk and Phatak (1984) and others. This work is also being carried out at N.A.E.C. by E. Foy.

3. BLUFF BODY AERODYNAMICS

i. Definition of a Bluff Body

A bluff body is one that ,for given flow conditions, has a massive separated region in its wake. In the Reynolds number range of about 10^4 and above, the flow over an airfoil at high angle of attack or over a cylinder or prism could be described as bluff-body flow. The most notable feature of a 3-D bluff-body flow is the usual presence of a complex vortex system in the wake that may be stationary or periodically shedding. Moreover, the flowfield is substantially altered by the presence of shear and turbulence in the free-stream flow. With a relative wind speed of 25 m/sec, a ship with a 17 m. beam has a beam-based Reynolds number of about $3x10^8$ and, because of its shape, would represent a 3-D bluff body.

Before speculating on the nature of ship airflows, it is pertinent to review the current state of two highly relevant areas : vortex shedding and free-stream turbulence effects.

ii Vortex Shedding From Bluff Bodies

Early observations of vortices were made by Leonardo da Vinci in the fifteen hundreds, Benard in the nineteen hundreds and ,early in this century, by Prandtl and Von Karman. Since then an impressive number of attempts have made to observe and analyze their motion. Surveys have been made by Parkinson (1974), Sarpkaya (1979) and Bearman (1984) and the attention here is largely focused on the areas that are likely to be applicable to ship airflows.

Some analytic and numerical work has been done in this field of vortex shedding from bluff bodies, but it can reasonably be said that most of the current information has been obtained experimentally. Until very recently, almost all of this work was carried out in "ordinary" wind tunnels that have negligible shear and free-stream turbulence. Much of what has been done in wind tunnels that simulate the earth's atmosphere, i.e. include both shear and some form of free-stream turbulence, has concentrated on the self-excited oscillations of tall slender flexible buildings or bridges on which the shedding of vortices changes the pressure distribution on the body, thereby causing it to move - mainly normal to the freestream flow direction. Furthermore, there has been a tendency to concentrate on the pressures and forces on the body, rather than on the details of the flowfield.

Because of the great mass of the ship, the fact that only a portion of it is subjected to the wind, and the low density of the air, it is unlikely that the airflow around the ship has any significant effect on the motion of the ship, thus the air flowfield is "forced" by the ship's motion.

An isolated 2-D body placed normal to a stream of fluid will, over a very wide range of Reynolds numbers shed vortices into its wake, due to the interaction of the shear layers as they detach from the body on opposite sides. The frequency at which these vortices are shed is called the "natural" shedding frequency and is given by $f = U\ S/D$, where U is the free-stream speed, D is a characteristic body dimension, usually the width, and S is the Strouhal number for shedding, which depends on the shape of the body and the Reynolds number. Blevins (1977,p18) shows this dependence for many different bodies. Typically S lies between 0.1 and 0.3 . Until recently it was believed that a splitter plate placed downstream of the body parallel to the free stream destroys these vortices ; then Smits (1982) showed that the wake consists of many vortices that may pair, triple or even quadruple. At the test low test Reynolds number of 1100, it was found that the reattachment eddies were not "split", but alternately deflected upstream and downstream. It is noteworthy that, in what is generally regarded as 2-D flow, recirculation cells with 3-D flow have been observed in the near wake of the body (Widnall, 1976).

Griffin (1981) has proposed a universal Strouhal number St* that collapses the characteristic wake scales of 2-D bodies in low turbulence (less than about one percent) flow onto a single curve for Reynolds numbers between 100 and at least 10^7. This number St* is f d / V, where f is the natural shedding frequency, d is the width of the wake at the end of the vortex formation region and V is the mean velocity at the edge of the separated boundary layer. It can be used to estimate the size of the wake.

A tall structure in the atmospheric boundary layer will shed vortices but, as its height is reduced, the shedding becomes weaker. There appears to be no shedding when the body is squat, for example, a cube.

When a body is forcibly oscillated normal to the free-stream direction, the natural shedding frequency can be altered by the so-called "lock-in" phenomenon, in which the vortices are shed at the frequency of the body. It occurs if the frequency of the body is within a certain frequency span that includes the natural shedding frequency. The extent of this span depends on both the shape of the body and and the amplitude of its oscillation. Bearman and Obasaju (1982) studied square section cylinders of side D with amplitudes of oscillation up to 0.25 D and found that the lock-in occurred in the reduced velocity band U / N D from 6.9 to about 12 ; here, N is the frequency of the imposed motion. The lock-in range was from 7 to 8 for amplitude 0.05 D and is expected to be greater than 6.9 to 12 for amplitudes larger than 0.25 D.

No studies could be found of bodies that were immersed in a shear layer and oscillated normal to the shear planes of the flow.

Nakaguchi, Hasimoto and Muto (1968) found that the drag coefficient of a 2-D rectangular cylinder, whose width (in flow direction) was about half the height, reached a value of almost 3, in contrast to the value of 2 for a flat plate or a square cylinder. Subsequently Bearman and Trueman (1972) established that the reason was the shedding of strong vortices into the wake. More recently Hucho (1976), in studying the influence of the slope of the rear of a "fast-back" car on the drag, found that a certain angle gave roughly the highest drag and smallest wake. Morel (1976) similarly found that there was a critical slope of the base of a body that gave a particularly large drag. In both cases, the reason was the shedding of strong vortices into the wake. Clearly, Aerodynamicists have to make some adjustments to the notion that the smaller the wake the lower the drag.

Sakamoto and Arie (1982), in studying the flow over a cubic prism set on the floor of a wind tunnel with a thick boundary layer , made interesting oil film pictures showing the presence of a horsehoe vortex wrapped about the foot of the prism and trailing downstream on either side of it, and two vortices in the wake, whose strength and location depended strongly on the orientation of the prism to the free stream direction ; these are shown in Figure 15. That a horseshoe vortex exists around the foot of a building, when wind blows normal to a face, has been known for many years.

Hunt, Abell, Peterka and Woo (1977) investigated the flow around a cube and established the presence of an inverted u-shaped vortex, whose ends

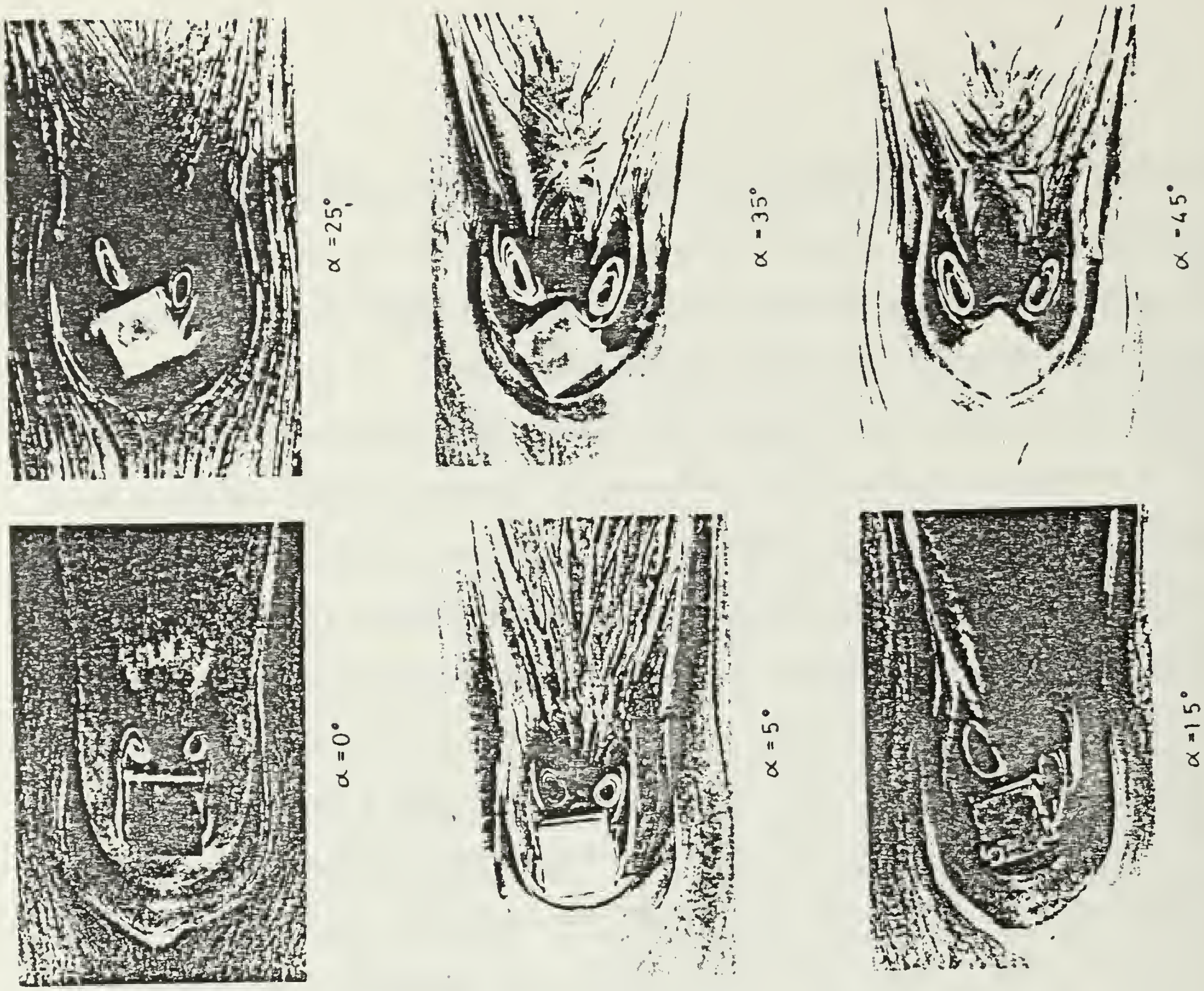


Figure 15

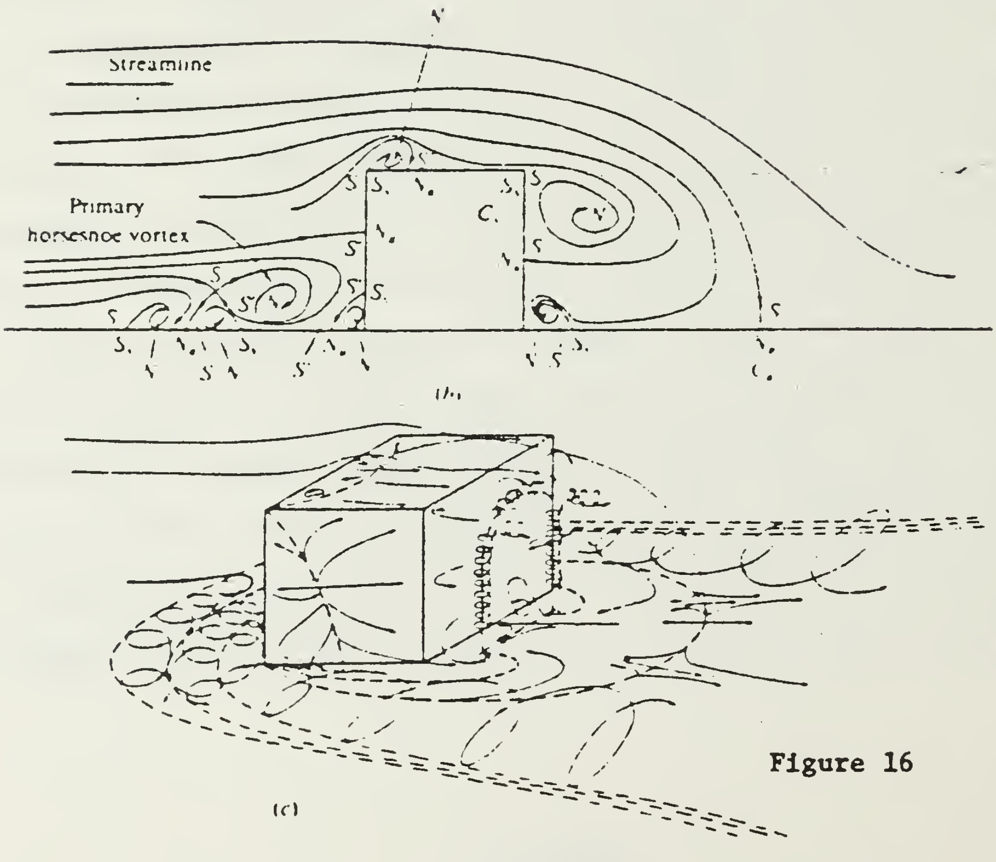


Figure 16

stay in contact with the ground at the rear of the cube (Figure 16). These ground contacts produced the oil streaks found by Sakamoto and Arie.

iii. The Influence of Freestream Turbulence

The Tay bridge in Scotland collapsed in a storm in 1880 and, subsequent to an inquiry, the British Board of Trade decided that future structures should be designed to withstand a wind pressure of 56 pounds per square foot of frontal area. Baker (1884) established that many existing structures would have collapsed under this pressure and set up wind pressure gauges in the form of vertical boards of different sizes. Over a period of years, the maximum pressure exerted on a board of 300 ft^2 was 19 lbs/ft^2, while on one of 1.5 ft^2, the maximum was 31 lbs/ft^2. This was probably the earliest demonstration that the influence of atmospheric turbulence on a structure depends on the spatial dimensions of the structure. Fage and Warsap (1929) showed that free - stream turbulence has a strong influence on the drag coefficient of a circular cylinder and that the mechanism of the turbulence lay in triggering the transition of the laminar boundary layer to a turbulent one. Thus , the equivalence of the effects of free-stream turbulence and an increased flow Reynolds number was discovered.

Many studies have since been done and foremost in these are Bearman (1972), Bearman and Obasaju (1982), Bearman and Morel (1983), Castro (1979,1981 and 1984) Castro and Robins (1977), Castro and Dianat (1983),Dianat and Castro (1984), Garthshore (1973,1984), Hunt (1973,1976), Durbin and Hunt (1979), Sakamoto and Arie (1983), Sakamoto and Oiwake (1984), Vickery (1966) and numerous others. Bearman and Morel give a substantial but incomplete bibliography.

Lee (1976) indicated that the length scale had a dramatic effect on the flow around a square prism. Petty (1979) studied the same body and concluded that, when wind tunnel blockage corrections are made, the effect is probably small. It should be noted, however, that rigorously verified blockage corections for bluff bodies in wind tunnels have not yet been established. Laneville and Williams (1979) determined that the length scale has a secondary effect and advise modeling of the mean flow profile and turbulence intensity in wind tunnel testing. Miyata and Miyazaki (1979) also report little influence of the length scale but indicate that it may be important when considering the unsteady motion of bodies.Earlier, however, Bearman (1971) decided that there were some scale effects.

Castro and Dianat (1983) studied both uniform smooth and sheared turbulent flow over rectangular blocks of height one unit, length (across the flow) of nine units and width one and two units. This is very relevant to the ship airflow and will be discussed in Subsection iv.

According to Bearman and Morel, Garthshore (1973) found that the effects of grid generated turbulence on a body could be reproduced by replacing the grid by a single small round rod, placed upstream of the body, that generated turbulence of the same intensity but smaller scale. It is the turbulence arriving at the body within a narrow region of about 2L wide on either side of the stagnation streamline that changes the development of the free shear layers as they leave the body.

Garthshore (1984) indicated that the effects of large scale turbulence is inconclusive, but that for small scale turbulence $L / D << 1$, the turbulence intensity is a more important parameter than the length scale . However, in the present problem, the ratio of the length scale to a characteristic dimension, L / D and L / H (H is the helideck height) lie between about four and twenty, which is much more like large scale turbulence, for which $L / D \gg 1$. In that same study, Garthshore found that the resonant amplitude of vortices shed from prisms can be substantially altered by freestream turbulence intensity. Bearman (1972) showed that there is some distortion of the turbulence as it approaches the body. The energy components parallel to the free-stream direction and normal to the body, are transferred into components parallel to the body. Hunt (1973) proposed a "rapid distortion" theory, which is based on the assumption that the changes in the turbulence, as it is convected past the body, are caused more by changes in the inviscid mean flow than by viscous and inertial effects. This implies that $\sigma / U \ll 1$ and $\sigma / U \ll L / D$. It has been concluded in Section 1 that the range of free-stream turbulence intensity likely to be encountered by a ship is below about 0.17 and Durbin and Hunt indicate that values up to 0.2 would just about qualify. Furthermore, the minimum L / D for the ship's beam or helideck height is likely to be about five. A further requirement is that the turbulence be isotropic, which is approximately the case for superstructure height, but it would not be valid near the sea surface.

This rapid distortion theory predicts that the high frequency components of the turbulence are amplified, while the low frequency ones are attenuated. As the most energetic turbulent eddies flow by the ship they are stretched in the flow direction largely by the inviscid mean flow.

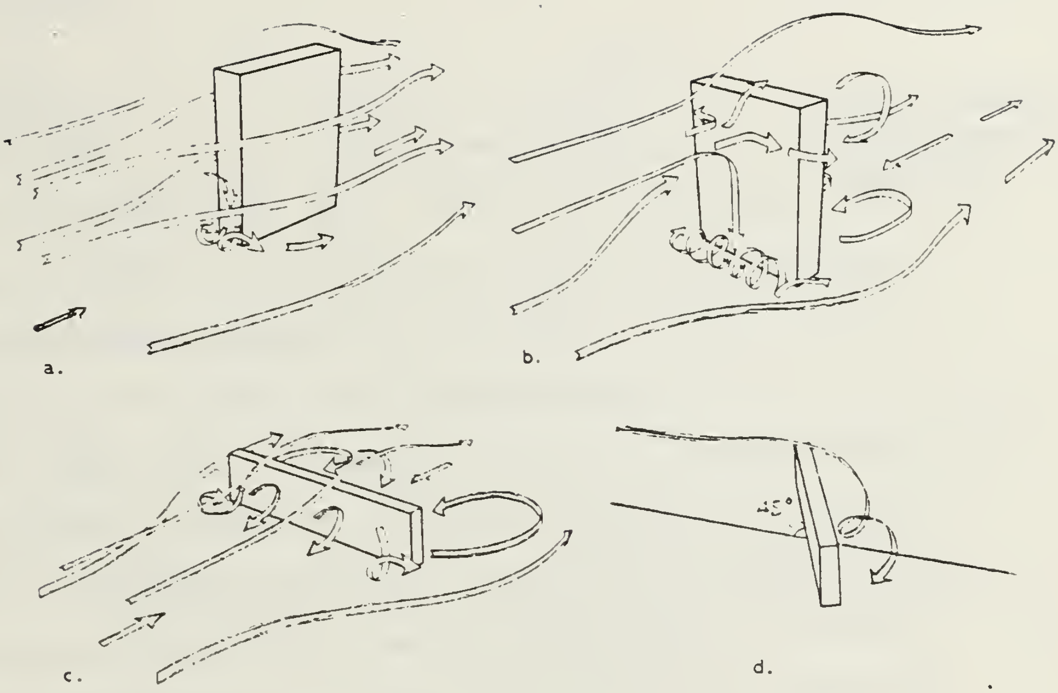
In general, the influence of free-stream turbulence on bluff-body flows changes the location of reattachment points and alters the flowfield around the body, by producing increased mixing near the separated shear layers.

iv. Some speculations about the nature of ship airflow

It appears that no significant numbers of measurements have ever been made of the airflow around a ship. Usual practice has been to take them at a few critical points near the landing decks and these give little information about the general flow patterns. For this reason, it is necessary to turn to other sources e.g. the aerodynamics of buildings. There has been considerable activity in this field for the past 10 - 15 years and reviews are given by Frost (1973) and by Cermak (1977). Beranek (1979) shows the general features of flow about isolated buildings of different aspect ratios and about clusters of buildings. Some flow patterns are shown in Figures 17 and 18.

The most likely, but exceedingly crude, model of the airflow around a ship is the flow around a building of about one unit high, ten units long and one about unit wide,representing the amount of the ship above the water line.

Figure (17c) shows the likely outer flow of a relative beam wind over this structure. A horshoe vortex wraps itself around the foot of the structure and trails downwind on both sides. The flow over the top is likely to be very complex and a very large recirculating zone is formed on the lee side. It is difficult to determine whether reattachment on top will occur. Dianat and Castro studied the flow near the surface of blocks one unit high, nine units long (cross wind) and one and two units wide (along wind) in a thin and a thick turbulent boundary layer ; the thin layer corresponds roughly to smooth uniform flow. They concluded that ; for the two unit wide block in the thick layer, there is almost certain reattachment ; for the one unit wide block in the thin layer, there is no reattachment and, for the



Airflow pattern around three types of single buildings.
a. Tall slender building.
b. Tall building of the transition type
c. Long building.
d. Long building, winddirection $\phi = 45^0$.

Figure 17

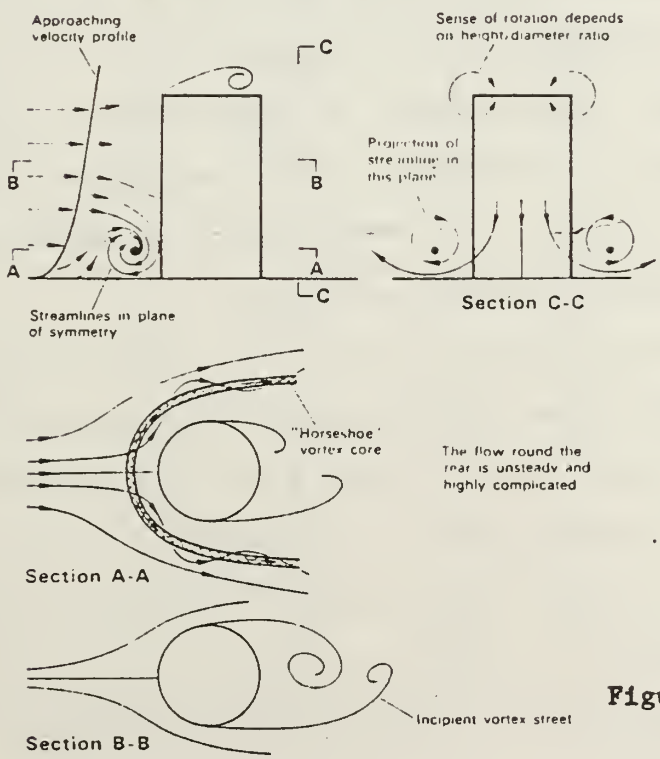


Figure 18

Much-simplified sketch of flow past an obstacle in a boundary layer (building in a wind).

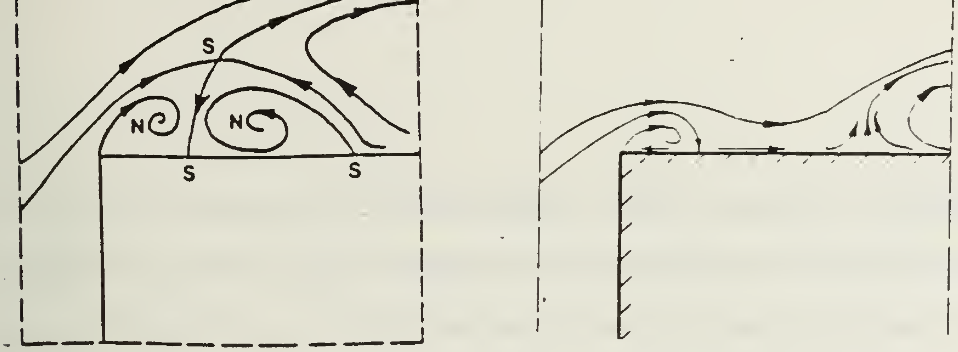
same block in the thick layer, there appeared to be intermittent reattachment. This work was carried out at a Reynolds number of $5x10^4$, based on body height and indicates little Reynolds number dependence. However, it is widely believed that when flows reattach, there is both Reynolds number and turbulence intensity dependence. The highly complex nature of the surface streamlines on the tops of the blocks is shown in Figure 19.

Whether or not the flow over the building that models the ship will reattach is somewhat inconclusive ; it probably depends on the width of the structure and also, to some extent, on the turbulence intensity.

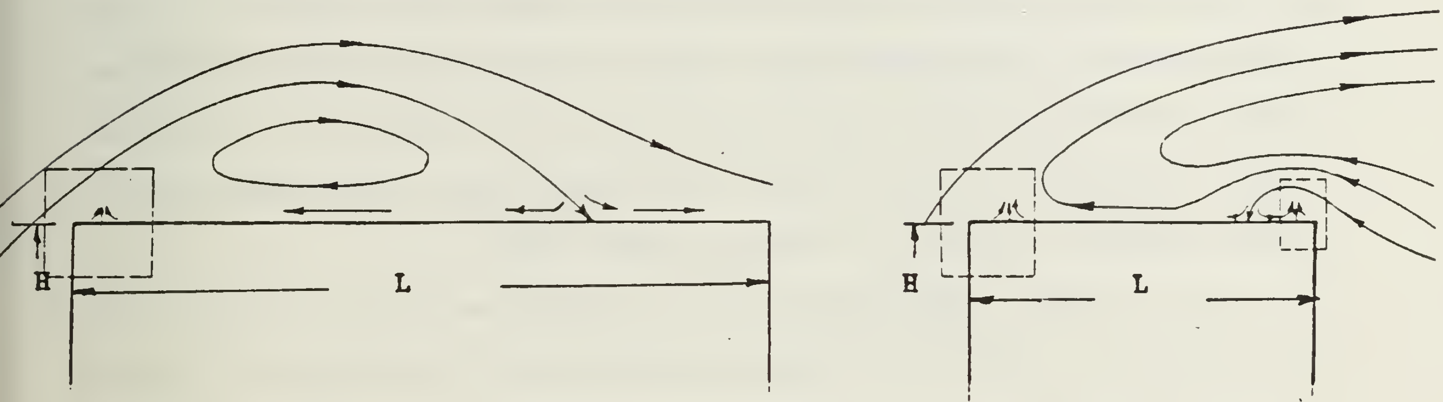
If now, this relative beam wind swings around towards the bow or stern, the symmetry is destroyed and the vortex around the foot vanishes. The probable outer flow pattern is shown in Figure 17d. A separated region is expected along the top windward edge, with reattachment now more likely. In both this and the beam wind case, it is probable that the flow over most of the structure is two dimensional.

The superstructure of most modern ships is usually cluttered with structures of different sizes and shapes e.g. lattice towers , antennas, exhaust stacks, etc. and the state of the wind after passing through these is beyond the wildest speculation.

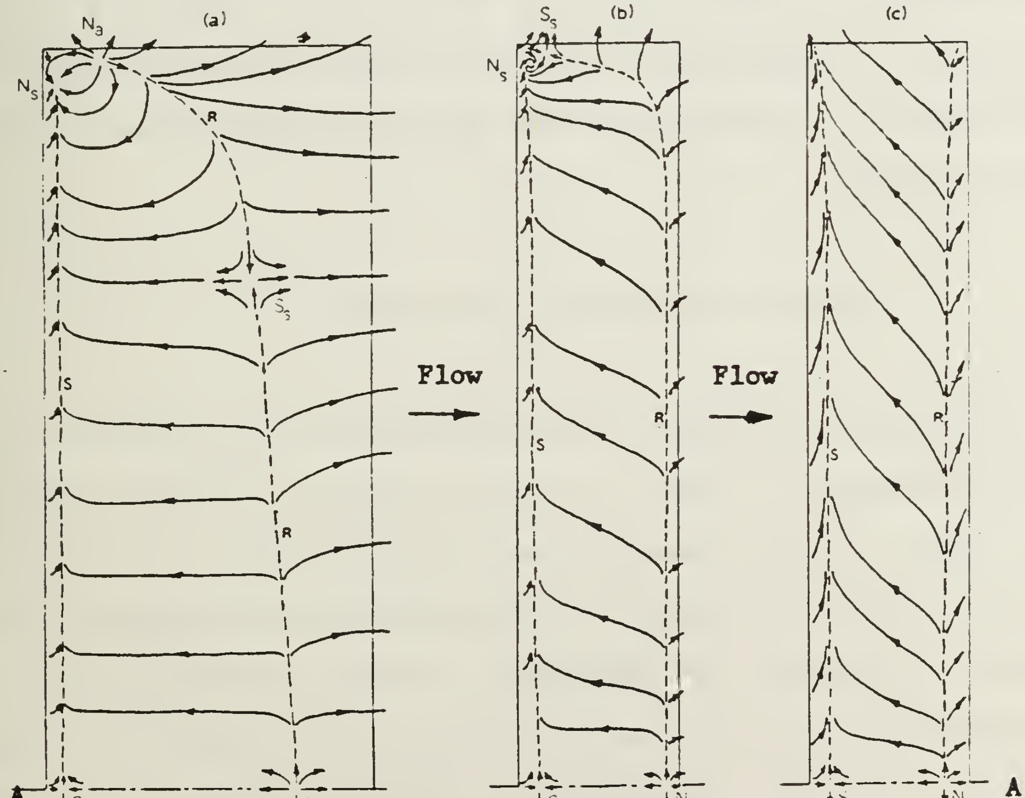
A real ship, of course, moves , with the two primary motions being roll and the coupled heave and pitch. The helideck height of the DD 963 above the mean water line is about 8.7 m. At maximum heave, the combined heave and pitch yields a total vertical motion of 4.8 m. or about 50 % of the height. This is a very large amplitude; Bearman and Trueman used a maximum value of 25 % for their prisms and information about larger amplitude motions appears to be non-existent, even in smooth uniform flow.



Flow at leading edge in plane A-A. (mid plane)



Flow in plane A-A. Case 1 Case 3



Surface streamlines, showing attachment nodes N_a, separation nodes N_s and separation saddle points S_s: (a) case 1; (b) case 2; (c) case 3. Flow is from left to right in each case, and only one-half ($y > 0$) of the symmetrical top surface flow is shown.

Case 1. L/H = 2 Rough B.L.

Case 2. L/H = 1 Rough B.L.

Case 3. L/H = 1 Smooth B.L.

Figure 19

It is probable, however, that, because of the sharp salient edges of the ship's bulwarks and the squat form of the major superstructure elements, e.g. the hangar, there will be little vortex shedding from a stationary ship in a high wind. As the latter two events are unlikely to occur simultaneously, the oscillating ship may well shed whatever stationary vortex structure exists in its wake, at its own frequency of oscillation. This oscillation may also cause a relatively stable reattachment point to become unstable, leading to a flapping shear layer.

It is also concieveable that, in certain conditions, the foot vortex may act as a ramp for an approaching beam wind, resulting in a very high wind over deck at certain points of the ship's heaving/pitching motion.

In conclusion, todays knowledge of the flow around a bluff body oscillating in a sheared turbulent layer is very sparse and a major effort will be required to gain an understanding of the highly complex nature of the ship's airwake.

v. Numerical Prediction of the Wake ?.

An excellent introduction to the Computational Fluid Dynamics of flows involving turbulence is given in a recent book by Bradshaw, Cebeci and Whitelaw (1981). It also considers the special problems of flows that have separation. This field is still in its infancy and the separation that can be handled at present is that from shapes that have rounded forebodies. The separation point must be supplied to the program in the form of an empirical relationship involving the free-stream turbulence intensity. The influence of length scale or the frequency-wise distribution of energy in the turbulence cannot be accounted for.

To handle bluff body wakes, empirical relationships, such as the one mentioned above, must be known and the present knowledge of bluff-body flows is inadequate in this respect. Recent attempts by Mahaffey, et al to apply the "Phoenics" CFD program of CHAM, has resulted in the prediction of flows that bear little resemblance to those shown in Figures 15,16 and 19 here.

4 THE HELICOPTER MOTION AND ITS SIMULATION

i The Helicopter Motion

Elementary introductions to helicopter theory are given by Gessow and Meyers (1952), Bramwell (1976) and Layton (1984). The former and the latter concentrate on performance, while Bramwell is primarily on stability and control. Johnson (1980) provides a more advanced analysis and Curtis, in a book by Dowell et al (1978) gives a very lucid account of rotor aeroelastic effects.

Helicopter blades are subjected to various motions superimposed on the general circular motion in the swept plane, such as flap (perpendicular to the plane), lag or lead-lag (about a radial line through its hub) and torsion (about the blade axis). The blades may be attached to the rotor in a number of different ways and the overall model must take this into account. Coupling may exist between the motions of the blades due to elasticity of the blade pitch control system or to the aerodynamic wake. It may also exist between the rotor and the fuselage in flight and between the rotor, fuselage and landing gear when on the ground. The bending-torsion coupling that can lead to flutter in aircraft wings is usually not a problem, unless the blades are swept. However, flap-lag coupling may occur and flap-lag stability is a serious consideration. Fortunately, numerous studies, most recently Prussing, Lin and Shiau (1984), indicate that atmospheric turbulence has a stabilizing effect on the motion.

The presence of compressibility effects and an unsteady rotor flowfield, even when the vehicle is moving with uniform speed, makes the analysis of the helicopter motion very complex. Furthermore, when operating within a few rotor diameters of the ground or a solid structure, significant influences on the handling qualities exist because of the "ground effect"; the latter occurs because the downwash from the rotor is effected.

Curtis, Sun, Putman and Hanker (1984), and Hanker and Smith (1985) are examples of recent studies of the ground effect. However, such research is usually confined to a plane ground without obstructions. Flight near the simplest bluff body - a cubical building - would be difficult to analyze, since even uniform flow past such a building is not yet well understood.

The equations of motion of helicopters of different configurations are given by Johnson (Chapter 15). Numerous mathematical models exist for specific vehicles ; for example, NASA TM's 81238, 84351 and 85890 provide the models for the CH53, CH47B and UH60 respectively. The Technical Memorandum by Talbot, Tinling, Decker and Chen gives a clear account of a mathematical model of a single main rotor helicopter for piloted simulation.

The inclusion of turbulence in the free-stream flow greatly complicates the analysis of helicopter motion. This is an on-going field of research, but a very slow one. At the 11th. European Rotorcraft Forum, held in September 1985, 102 papers were presented. Two of these were concerned with gust loading and only one with a random turbulent flow.

Early studies of the effects of turbulence on the flow through rotors, for example Lakshmikantham and Rao (1972) and Arcidiacono, Bergquist and Alexander (1974), considered discrete gusts only. These are sudden or gradual increases in the free-stream speed up to a certain magnitude and are purely deterministic. Recent attempts at including random turbulence into the rotor flowfield were made by Azuma and Saito (1982) and Prussing et al. The former uses an analysis based on local momentum theory and compares the results with those from an experimental investigation.This method allows the prediction of the azimuthal or timewise loading of the blade as the gust is penetrated. In addition, the spectral density of the blade response can be computed for any kind of gust input. The flapwise and chordwise bending and torsional deflections were expressed in the commonly used modal expansion series and the equations were solved using the Holzer - Myklestad procedure. The aerodynamic loading was expressed through the method well known to Aeroelasticians - the Wagner and Kuessner functions - and the random gusts were expanded in Fourier series. The results show that the unsteady gust effects cause no appreciable response in the mean quasi-steady flow. This implies little effect on the rotor thrust. Prussing et al , using white noise* as the random fluctuation, similarly found that the mean response of the rotor was not significantly altered by the turbulence. In contrast, however, r.m.s. responses of the rotor representing fluctuations away from the average, were significantly affected.

A very useful paper on the effects of turbulence on the whole helicopter and the simulation thereof, is by Dahl and Faulkner (1979). They also discuss the need for a non-Gaussian model of atmospheric turbulence and appear to be unaware of the report by Reeves, Joppa and Ganzer (1976).

To date, the analysis of helicopter response to a turbulent free-stream has been confined to simple single-rotor configurations ; further research

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* White noise here represents random turbulent fluid motion that has a uniform energy spectrum i.e. energy is present in equal amounts at all frequencies. Filters are usually used to taper off the energy at the high and low frequency limits.

is needed to clarify the response of all of the eleven different helicopters and rotor-configurations in the list given by Carico and Madey.

ii. Simulation of the Helicopter Motion

While much work remains to be done before the picture is complete, lack of such details have not prevented attempts at simulation of the helicopter motion. Reichert and Rade (1973) indicate that simple models are adequate for simulating the stability and control aspects of flight, and for determining the loads in steady flight, maneuvers and gusts. They also present the results of a simulation that includes the Dryden model of atmospheric turbulence. This model is analytically simpler than the Von Karman one (compare Equations 6 and 7), but is less accurate, as shown in Figure 5.

One important outstanding problem in helicopter analysis is to determine to what degree the mathematical model can be simplified, while still retaining adequate fidelity. McFarland (1982) considers this problem and discussions also appear in the papers by Statler and Deel (1981); Reichert and Rade; Key, Hanson, Cleveland and Abbott (1982) and Huber, Dahl and Inglsperger (1985).

Simulation fidelity has long been recognized as a difficult problem and it was addressed by an AGARD working group AMP/FMP WG-10. Discussions also appear in the last three papers mentioned above and in one by Bray (1982), who gives the NASA Ames Research Center's perspective. This TM, which is purely descriptive, presents a substantial discussion of various kinds of cueing for both land and ship-board operations and the cockpit motion requirements. Validation of a helicopter model requires that both quantitative and qualitative correlations be obtained ; the former compares data from a real helicopter with the model prediction and the latter is the opinion of experienced pilots.

Realistic simulation of the motion of a helicopter not in ground effect requires initially that the free-stream conditions - at least the mean velocity profile, the turbulence intensity and spectrum function be known as functions of time and space. The most common model divides the blades into segments and, using blade element theory, computes the forces on each segment and sums them to obtain the force on the rotor at discrete points in time. The forces on the fuselage are usually taken from a data base that has been obtained from wind-tunnel data. All this must be integrated into other models of the helicopter power plant and of the audio and visual systems.

The overall simulation thus requires a great deal of computation and, if the helicopter is flying through a region of space, e.g. the airwake of a ship, where the gradients in the air variables are high, then very high speed computation is required for real-time simulation.

The fastest computer used by either NASA Ames Research Center or the Army Aeromechanics Laboratory is the CDC 7600. At the present time neither has plans to move to a more powerful one. Statler and Deel claim that their Aeromechanics Laboratory has the most advanced ground-based simulator in the world and that it is not capable of simulating nap-of-the-earth operations.

The most optimistic report of simulation of helicopter motion is by Huber et al at MBB in Germany ; they claim that their model was highly rated by pilots and the graphs they give for comparison of the model predictions with real data are impressive indeed. The image generator is a General Electric CGI-Compu-Scene II that allows 8000 edges per scene with a field of view 106 degrees horizontal and 23 degrees vertical from up to five channels ; they used three then but plan to update to five. It has a frame rate of 30/sec, 256 colors, has a brightness of 6 foot Lamberts, a resolution of 1 m rad. and can provide three moving targets in simulated day, dusk or night. Most importantly, it allows shading, edge smoothing and the texturing necessary to provide visual cues to distance.

According to Huber et al, the MBB simulator uses non-linear aerodynamics, rigid body and rotor dynamics and considers the fuselage, tail-rotor and empennages in a realistic way. The rotor model is based on blade element theory that includes the effects of compressibility and stall. The rotor downwash is modeled by a modified momentum theory, that is adjusted for ground effect by reducing it by a function of the rotor to ground separation. The analysis of the rotor dynamics is limited to a certain frequency band, the limits depending on what is being simulated. For example, if aeroelastic effects were of no interest, a low-pass filter that cut off frequencies above about ten Herz is used. To model the rotor and body modes coupling, each blade was considered separately. A Denelcor Inc., Heterogenous Element Processor with ten parallel processors is used, with one processor for each of the four rotor blades. The atmospheric turbulence is represented by the Dryden spectrum (Equation 7) and deterministic gusts can also be handled. By inflating cushions on the cockpit seat and backrest, translational and rotational accelerations are simulated within a frequency range of zero to three Herz. The buffeting system allows simulation of vertical accelerations and vibrations up to ±2 g with a frequency range of 3 to 35 Hz.

Table 1, taken from Dongarra (1984), gives a comparison of the speed of the fastest computers available today, when doing typical engineering type calculations; the term "Megaflops" is the number of millions of floating

Solving a System of Linear Equations with LINPACK[a] in Full Precision[b]

Computer	OS/Compiler[c]	Ratio[d]	MFLOPS[e]	Time secs	Unit[f] μsecs
CRAY X-MP	CFT (Coded BLAS)	.36	33	.021	0.061
CDC Cyber 205	FTN (Coded BLAS)	.48	25	.027	0.079
CRAY X-MP	CFT (Rolled BLAS)	.57	21	.032	0.093
Fujitsu VP-200	Fortran 77 (Comp directive)	.64	19	.040	0.11
CRAY-1S	CFT (Coded BLAS)	.54	23	.030	.088
Fujitsu VP-200	Fortran 77 (Rolled BLAS)	.72	17	.040	0.12
Hitachi S-810/20	FORT77/HAP (Rolled BLAS)	.74	17	.042	0.12
CRAY-1S	CFT (Rolled BLAS)	1	12	.056	0.16
CDC Cyber 205	FTN (Rolled BLAS)	1.5	8.4	.082	0.24
NAS 9060 w/VPF	VS opt=2 (Coded BLAS)	1.8	6.8	.101	0.28
Fujitsu M-380	Fortran 77, opt=3	1.9	6.3	.109	0.32
CDC Cyber 875	FTN 5 opt=3 (Coded BLAS)	2.2	5.5	.124	0.36
NAS 9060	VS opt=2	2.3	5.3	.130	0.29
CDC Cyber 875	FTN 5 opt=3	2.6	4.8	.143	0.42
CDC 7600	FTN (Coded BLAS)	2.6	4.6	.148	0.43
CDC Cyber 176	FTN 5.1 opt=2	2.6	4.6	.148	0.43
Amdahl 5860 HSFPF	H enhanced opt=3	3.1	3.9	.176	0.51
Amdahl 5860 HSFPF	VS opt=3	3.2	3.8	.181	0.53
CDC Cyber 760	FTN 5, opt=3 (Coded BLAS)	3.3	3.7	.186	0.54
CDC 7600	FTN	3.8	3.3	.210	0.61
CDC Cyber 760	FTN 5, opt=3	4.7	2.6	.260	0.76
FPS-164	D, opt=3 (Coded BLAS)	4.7	2.6	.264	0.77
IBM 370/195	H enhanced opt=3	4.9	2.5	.275	0.80
IBM 3081 K	H enhanced opt=3	5.7	2.1	.321	0.94
CDC Cyber 175	FTN 5 opt= 2	5.8	2.1	.322	0.94
IBM 3081 K	VS opt=3	6.2	2.0	.346	1.01
CDC 7600	Local	6.4	2.0	.359	1.05
CDC Cyber 175	FTN 5 opt=1	6.8	1.8	.381	1.11
IBM 3033	H enhanced opt=3	7.0	1.8	.390	1.14
IBM 3033	VS opt=3	7.1	1.7	.396	1.15
IBM 3081 D	VS opt=3	7.4	1.7	.415	1.21
Amdahl 470 V/8	H enhanced opt =3	7.7	1.6	.429	1.25
Amdahl 470 V/8	VS opt=3	8.2	1.5	.458	1.33
FPS-164	D, opt=3	9.5	1.3	.529	1.54
CDC 7600	CHAT, No opt	9.9	1.2	.554	1.61
IBM 370/168 Fast Mult	H Ext	10	1.2	.579	1.69
Amdahl 470 V/6	H opt=2	11	1.1	.631	1.84
IBM 4381	VS opt=3	13	.96	.718	2.09
IBM 370/165 Fast Mult	H Ext	16	.77	.890	2.59
Harris 1000	Vos 3.3 opt g (Coded BLAS)	22	.57	1.21	2.16
CDC 6600	FTN 4.6 opt=2	26	.48	1.44	4.19
CDC Cyber 170-835	FTN 5 opt=2	26	.47	1.45	4.22
CDC Cyber 170-835	FTN 5 opt=1	28	.44	1.57	4.58
Harris 1000	VOS 3.3 opt g	30	.41	1.67	4.86
UNIVAC 1100/81	ASCII opt=ZEO	32	.38	1.80	5.24
Concept 32/8750	UTX/32	34	.36	1.88	5.48

Table 1

CDC 6600	RUN	34	.36	1.93	5.62
Data General MV/10000	f77 opt level 2	40	.30	2.26	6.58
IBM 4361	VS opt=3	41	.30	2.31	6.73
Harris 800	Fortran 77	53	.23	2.99	8.70
IBM 370/158	H opt=3	53	.23	2.99	8.71
VAX 11/785 FPA	VMS (Coded BLAS)	54	.23	3.01	8.77
IBM 370/158	VS opt=3	56	.22	3.15	9.17
CDC Cyber 170-720	FTN 5. opt=2	62	.20	3.47	10.1
Itel AS/5 mod 3	H	63	.19	3.54	10.3
NORSK DATA ND-500	Fortran-500-E	63	.19	3.54	10.3
CDC Cyber 170-825	FTN 5. opt=2	65	.19	3.63	10.6
IBM 4341 MG10	VS opt=3	66	.19	3.70	10.8
VAX 11/785 FPA	VMS	68	.18	3.79	11.0
CDC Cyber 170-825	FTN 5. opt=1	68	.18	3.81	11.1
CDC Cyber 170-720	FTN 5. opt=1	70	.17	3.93	11.4
VAX 11/780 FPA	VMS (Coded BLAS)	76	.16	4.25	12.4
ICL 2988	f77 OPT=2	85	.14	4.78	13.9
VAX 11/750 FPA	VMS (Coded BLAS)	88	.14	4.92	14.3
VAX 11/780 FPA	VMS	94	.13	5.28	15.4
CONCEPT 32/6750	UTX/32	99	.17	5.53	16.1
VAX 11/780 FPA	UNIX 4.2 BSD f77	101	.12	5.67	16.5
CDC 6500	FUN	102	.12	5.69	16.6
Denelcor HEP	f77	107	.11	5.98	17.4
Prime 750	Primos f77 v19.1	107	.11	6.00	17.4
VAX 11/750 FPA	VMS v3.4	113	.10	6.87	20.0
VAX 11/750 FPA	UNIX 4.2 bsd f77	128	.096	7.15	20.8
Prime 850	Primos	130	.095	7.26	21.1
UNIVAC 1100/62	ASCII opt=ZEO	132	.093	7.38	21.5
Data General MV/8000	f77 opt level 2	157	.078	8.80	25.6
Ridge 32	f77	179	.068	10.0	29.2
Apollo DN 460	FTN opt	208	.059	11.6	33.8
VAX 11/750	VMS v3.4	215	.057	12.1	35.1
HP 9000 Series 500	Fortran 1.7	285	.043	16.0	46.6
VAX 11/730 FPA	VMS (Coded BLAS)	286	.043	16.0	46.6
VAX 11/725 FPA	VMS (Coded BLAS)	286	.043	16.0	46.6
Apollo PEB	4.1 (Coded BLAS)	323	.038	18.1	52.7
IBM 4331	H opt=3	326	.038	18.3	53.2
Pyramid w/o FPA	f77	334	.037	18.7	54.5
VAX 11/730 FPA	VMS	348	.036	19.5	56.9
VAX 11/725 FPA	VMS	348	.036	19.5	56.9
Prime 2250	Fortran 77	365	.034	20.5	59.6
IBM PC-XT/370	H opt=3	391	.031	21.9	63.7
VAX 11/750	UNIX 4.2 bsd f77	422	.029	23.7	69
Masscomp MC500 w/FP	UNIX. f77 opt	452	.027	25.3	73.7
SUN 2 + SKY board	UNIX. f77 opt	557	.022	31.2	90.1
Apollo PEB	4.1	559	.022	31.3	91.2
Canaan	VS	588	.021	33	96
Chas. River Data 6835 + SKY	SVS Fortran 77	700	.018	39.2	114
Cadtrak DS1/8087	Intel Fortran 77	1143	.011	64	186
IBM PC/AT	Microsoft 3.2	1341	.0091	75.1	219
Chas. River Data 6835	SVS Fortran 77	1401	.0088	78.5	229
IBM PC/XT	Microsoft 3.2	1766	.0069	98.9	288
HP 9000 Series 200	HP-UX	1982	.0062	111	323
SUN 2	UNIX. f77 opt	1991	.0062	112	325
Masscomp MC500	UNIX. f77 opt	2588	.0047	145	422
SUN	UNIX. f77 no opt	2661	.0046	149	434

Table 1

point operations per second. From it, it is clear that the speed of a computer depends on which compiler is used with it. The Denelcor HEP that gives MBB such good results, has a speed of about 1 % of the Cray 1s, and is slower than the slowest VAX 11/780. The CDC 7600, which is used by N.A.S.A. Ames / Army Aeromechanics Lab. has, in its slowest configuration, a speed of about 10 % that of the Cray 1s. and in its fastest 38 % of it.

This picture, however, can be misleading. Hodges (1986) recently had a computer program, that calculated the aeroelastic stability characteristics of arbitrary rotorcraft configurations, running on a CDC 7600. When this was switched to a Cray 1s, it ran much slower and, only after considerable re-configuration, did it run faster on the Cray.

To complicate things still further, Lubeck, Moore and Mendez (1985) indicate that the speed at which a particular program will run may also depend on the computer workload, thus making benchmark comparisons even more difficult.

All this greatly complicates the choice of computer. If the latter is to be dedicated to simulating the interface, then it is desirable that the computer program be constructed in advance of choosing the computer. Only by configuring the program to the architecture of several computers and running it by itself on each, can the best choice be made. It is possible that a slower, less expensive, computer will be adequate.

iii Simulating the Ship Environment

There are in existence numerous simulators that purport to simulate the operations of helicopters in the environment of the ship. The "ship deck" of the Sikorsky simulator oscillates sinusoidally only. Although promised information by Bell Helicopter, none was available at the time of ending this report. Fortenbaugh (1978), then of the Vought Corp. assembled a simulator program that is based on an early (1976) DTNSRDC ship motion program and the Boeing Vertol airwake model of the frigate FF 1052. Turbulence was represented by filtered white noise. He also used "Strouhal* scaling", "....to permit different size ships with similar structures and flight deck locations to be represented with the FF 1052 data base". He then applied the scaling to the the FF 1052 measurements to obtain the wake of the DD 963. This is an incredibly crude process and can be expected to provide reasonable results for a ship and its exact scale model only. The above airwake model was discussed previously in Sec. 1 v. and, when this faulty wake is applied to the DD 963 by this Strouhal "distortion", the results can be expected to be as accurate as picking random numbers !. The most recent and comprehensive account of simulating the helicopter/ship interface is the paper by Paulk, Astill and Donley (1983). The helicopter concerned was the SH-2F and the ship was the the DD 963. Unfortunately, they used the airwake model derived by Fortenbaugh. They found that "...both the standard deviation and frequency content of the airwake were excessive....and.....two characteristic far-field air disturbances generated by the stacks of the DD 963 and normally encountered during a 30 degree to port or starboard approach were absent". Hardly surprising !. In general, however, they found fairly good correlation between the predictions of the

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* Equality of Strouhal number (See Sec 3 ii) is required for dynamic similarity of two time dependent flows.

model and actual helicopter data. They note that improvements need to be made to the model and the visual system and that validation against flight data for the SH-2F is needed. They also indicate that improvements and validation are required for the airwake model.

iv The Computer Size for Simulation

The question of computer size for simulating the interface cannot be answered at this time. The ship airwake must first be determined. Meanwhile, more work of the kind undertaken by McFarland, Key, et al and Huber, et al must be done in order to determine to what degree the mathematical model and the complex turbulent flowfield can be simplified, while still retaining the required fidelity of the helicopter motion. If the MBB simulator is as good as described by Huber, et al , there is reason to be optimistic.

5 CONCLUSIONS AND RECOMMENDATIONS

1. The condition of the free-stream airflow to the ship can be determined with sufficient accuracy.

2. The DTNSRDC's ship motion program is a good basic one that needs some further development and, in particular, validation with a variety of different size real ships. The latter is a difficult task, in view of the fact that real waves do not quite conform to the Bretschneider spectrum. The DTNSRDC seems well equiped to undertake this work.

3. The ship airwake is highly complex, virtually unknown, and will require a major effort to understand. Future airwake studies should address the ship anemometer interference problem. Research into airwakes, funded by the Air Vehicle Division of the Naval Air Systems Command, is currently under way at the Naval Postgraduate School.

4 Future interface tests should measure and publish either the true wind velocity or the true ship velocity, in addition to the relative velocity.

5 The motion of helicopters can be predicted reasonably well, so long as the velocity gradients that envelop it are not too large. The motion in regions where the gradients are high, for example,

when entering or leaving the wake of a building or a ship's superstructure, will require a good deal of study. Such research is essential to the future of accurate simulation.

6. The pace of research into turbulence modeling is very slow and needs acceleration. Before a decision can be made on the size of computer required for simulation of the interface, additional studies are required to determine to what extent the mathematical model of the helicopter and the physical model of the complex fluid flowfield can be simplified, while still retaining sufficient fidelity of the simulation. Benchmark tests for computer speeds can be misleading. It would probably be best to construct the computer program for the simulation of the interface in advance of the computer choice. If a dedicated computer is to be chosen, this process can be assisted by configuring the program to the architecture of several candidate computers and running it by itself. If sharing the computer with other users is envisioned, then the test should be made by applying some realistic loading to the computer while the simulation is in progress.

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